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Krissek, L.; Browne, G.; Carter, L.; Cowan, E. A.; Dunbar, G.; McKay, R.; Naish, T.; Powell, R. D.; Reed, J.; Wilch, T.; and ANDRILL-MIS Science Team, "Sedimentology and Stratigraphy of the AND-1B Core, ANDRILL McMurdo Ice Shelf Project, Antarctica" (2007). *ANDRILL Research and Publications*. 22.
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Sedimentology and Stratigraphy of the AND-1B Core, ANDRILL McMurdo Ice Shelf Project, Antarctica

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Abstract - During the 2006–2007 austral season, the ANDRILL McMurdo Ice Shelf Project recovered a core 1285 m-long (AND-1B) from Windless Bight in the McMurdo Sound region. This core contains a range of lithologies, including both siliciclastic and volcanic diamictites, sandstones and mudstones; diatomites; and volcanic ash/tuff and one phonolitic lava flow. The succession has been subdivided into eight lithostratigraphic units and 25 subunits, based on lithological abundances. Eleven lithofacies have been recognized, ranging from open marine diatomites and mudstones to turbidites to ice-proximal massive and stratified diamictites. More than 60 glacial marine sequences have been recognised, bounded by glacial surfaces of erosion. Three distinct facies stacking patterns are present, showing evidence of glacial advance/retreat/advance with varying degrees of preservation. Carbonate and pyrite are the dominant secondary phases in the core. The pyrite overprint is especially notable in volcanic sediments below ~400 metres below seafloor (mbsf), where it often obscures stratification and sediment texture.

INTRODUCTION AND OVERVIEW

This chapter presents the results of sedimentologic description/study and lithostratigraphic subdivision of the AND-1B core. The detailed core descriptions are shown as graphic logs at a scale of 4 m/page and are available online at <http://www.mna.it/english/Publications/TAP/terranta.html> (Section 'Downloadable files'). Summary logs, at a scale of 100 m/page, are included here as figure 1. Additional summary logs, at scales of 650 m/page and 1285 m/page, have been generated and are used elsewhere in this report by other discipline teams. The core has been divided into eight lithostratigraphic units on the basis of major changes in lithology recognised during core description. This division draws attention to the relative importance of prominent lithologies, such as diamictites, diatomites, and volcanic sediments and rocks. The eight major lithostratigraphic units are divided further into a total of 25 lithostratigraphic subunits on the basis of smaller-scale lithologic changes. In addition to changes in the relative abundances of diamictites, diatomites, and volcanic sediments/rocks, changes in the relative abundances of sandstones and mudstones have been used to define lithostratigraphic units.

Eleven recurring lithofacies have been recognised in the AND-1B core on the basis of a lithology or

an association of lithologies, bed contacts and bed thicknesses, sediment texture, sedimentary structures, and, to a lesser extent, colour. The entire facies assemblage is interpreted to record marine to subglacial environments of deposition. Facies 1 (diatomite) is interpreted to record pelagic sedimentation in an open marine environment, although sometimes affected by iceberg rafting. Facies 2 (mudstone, primarily massive) is interpreted to record environments dominated by hemipelagic suspension settling, which may be either distal or proximal to grounded ice. Siltstone and sandstone laminae within Facies 2 may represent the minor influence of distal sediment gravity flows, winnowing by bottom currents, or settling from turbid plumes; future research may reveal which of these, if any, carries a signal of glacial proximity. Coarser sediments (poorly sorted sands and limestone clasts) record the influence of ice rafting, at least episodically. Facies 3 (interstratified mudstone and sandstone) is similar to Facies 2 but with an increased importance of sandstone interbeds. This interbedding is interpreted to record the combination of hemipelagic sedimentation and distal to proximal sediment gravity flows, sourced either from grounding line processes or volcanic/tectonic activity. Ice rafting and traction currents may have supplied or modified the coarser-grained component in Facies 3.

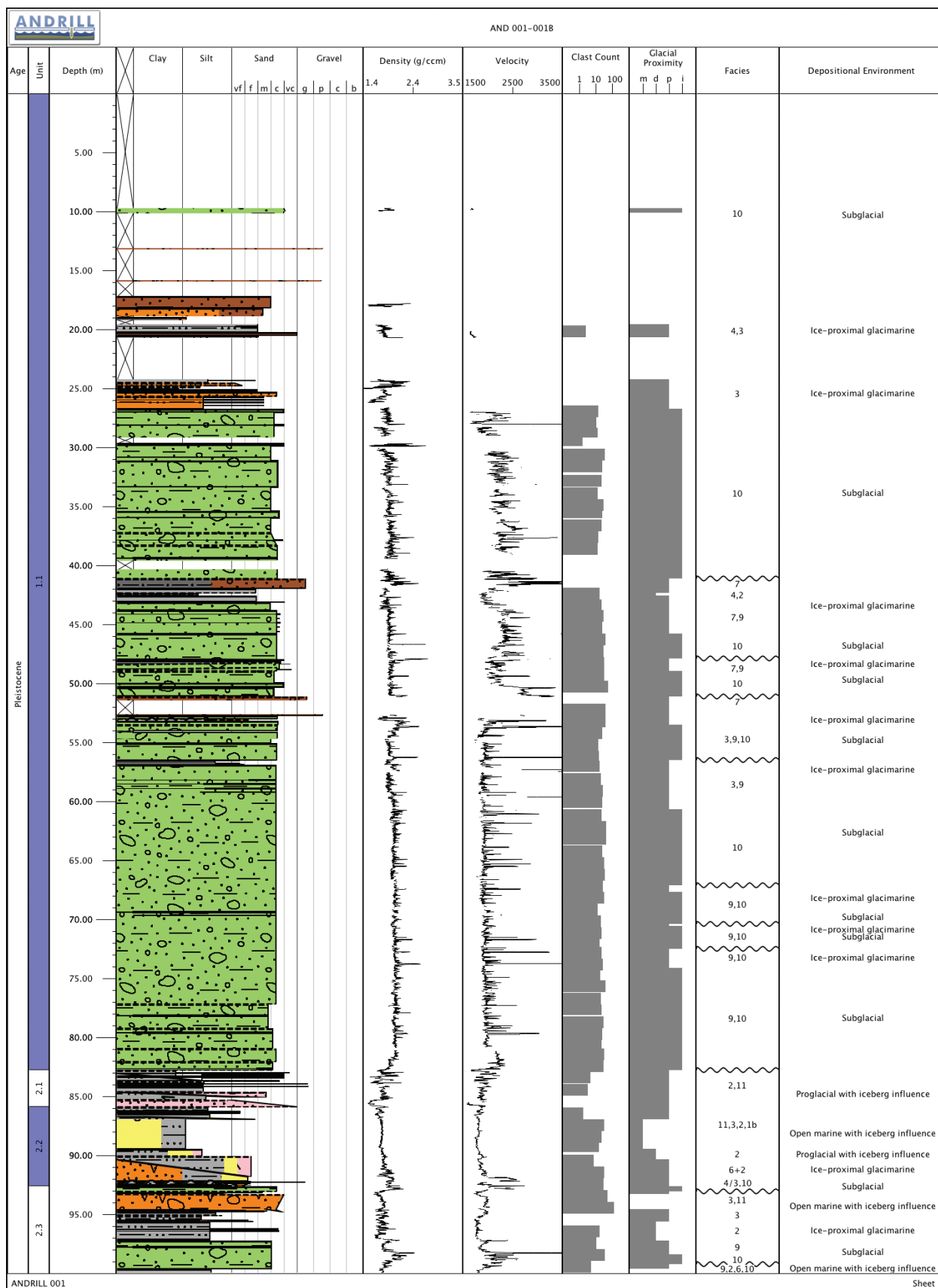


Fig. 1 – Graphical logs of the sedimentary sequence recovered at AND-1B, showing lithostratigraphic subdivisions.

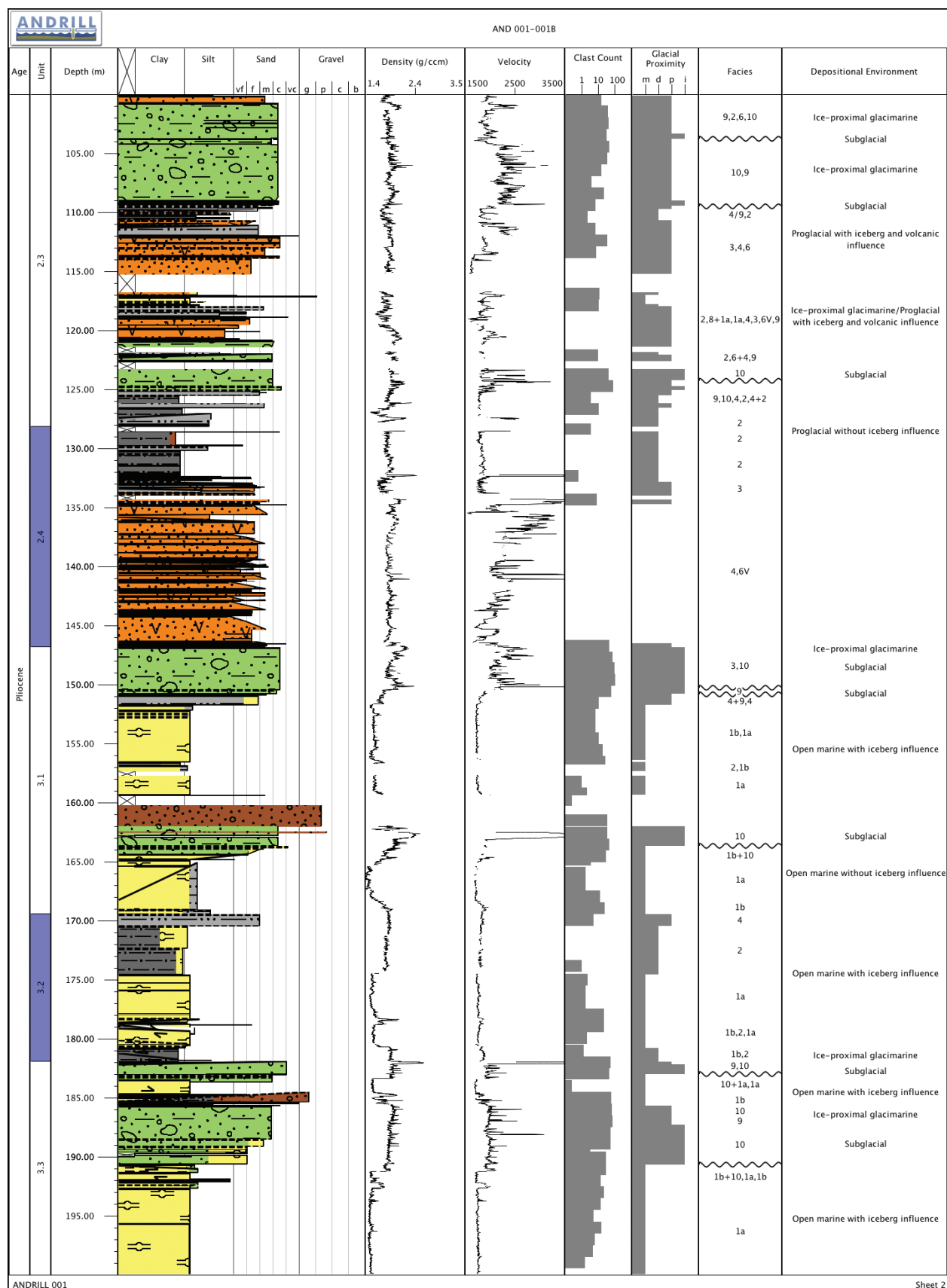


Fig. 1 – Continued.

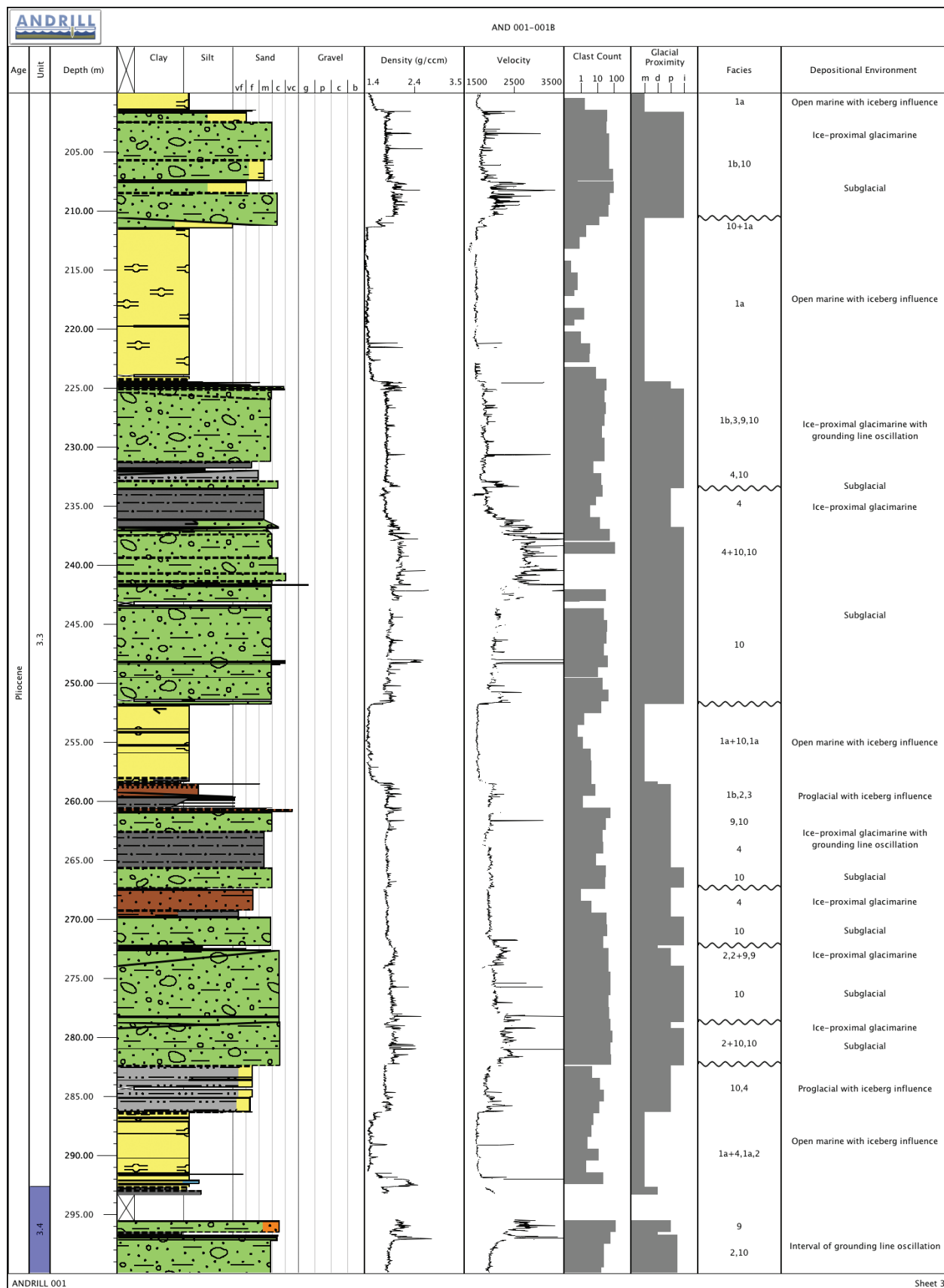


Fig. 1 – Continued.

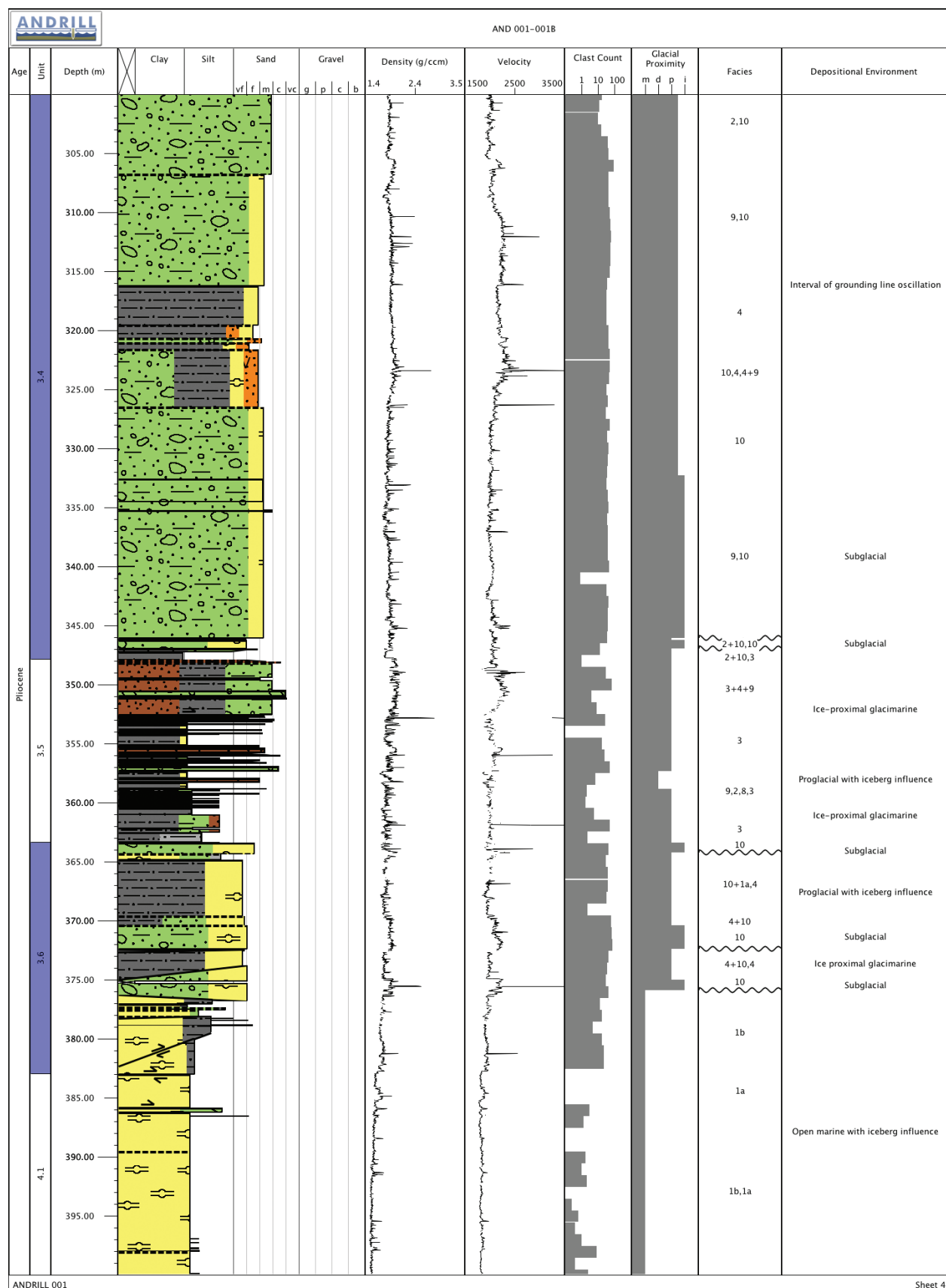


Fig. 1 – Continued.





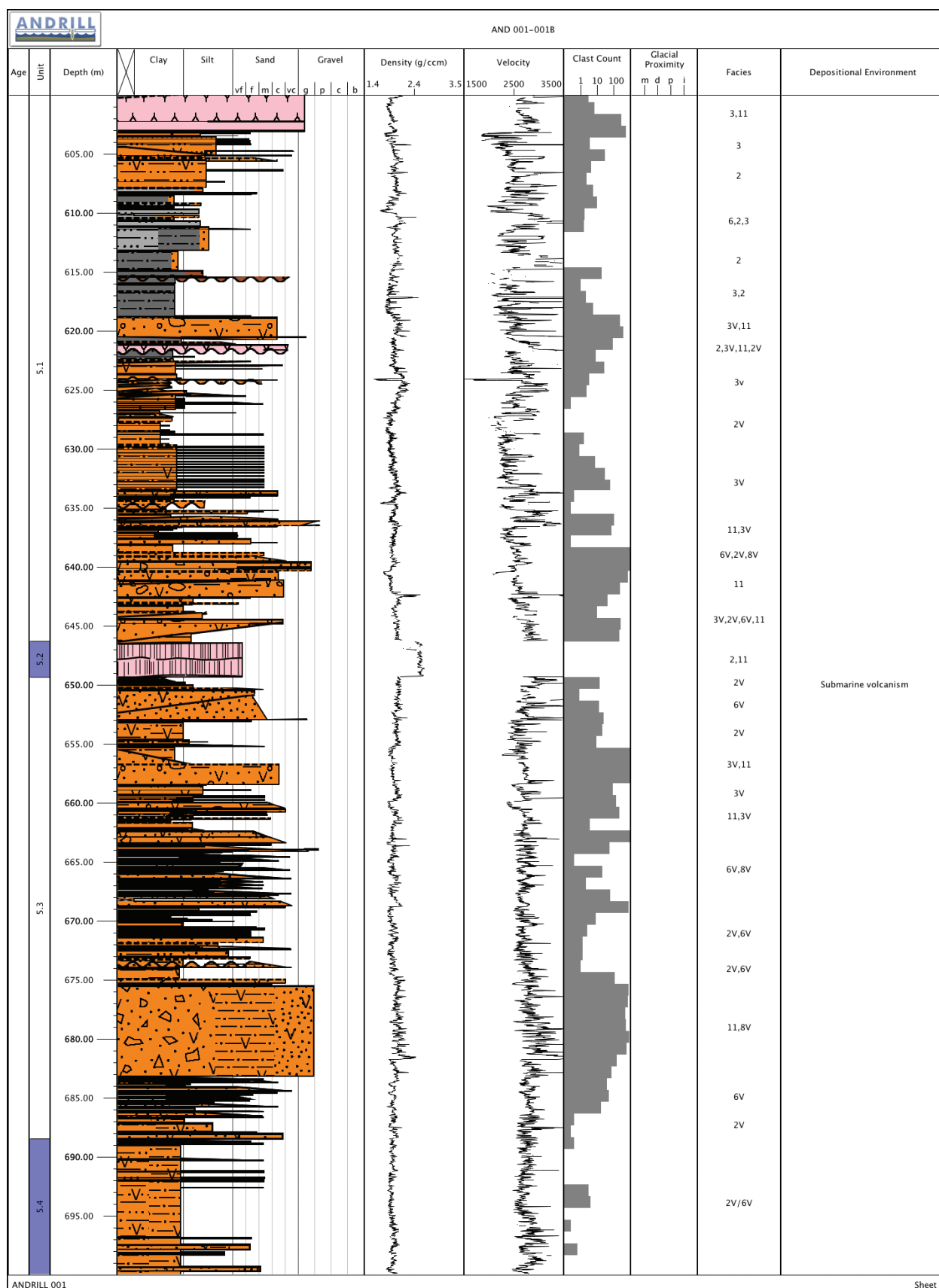


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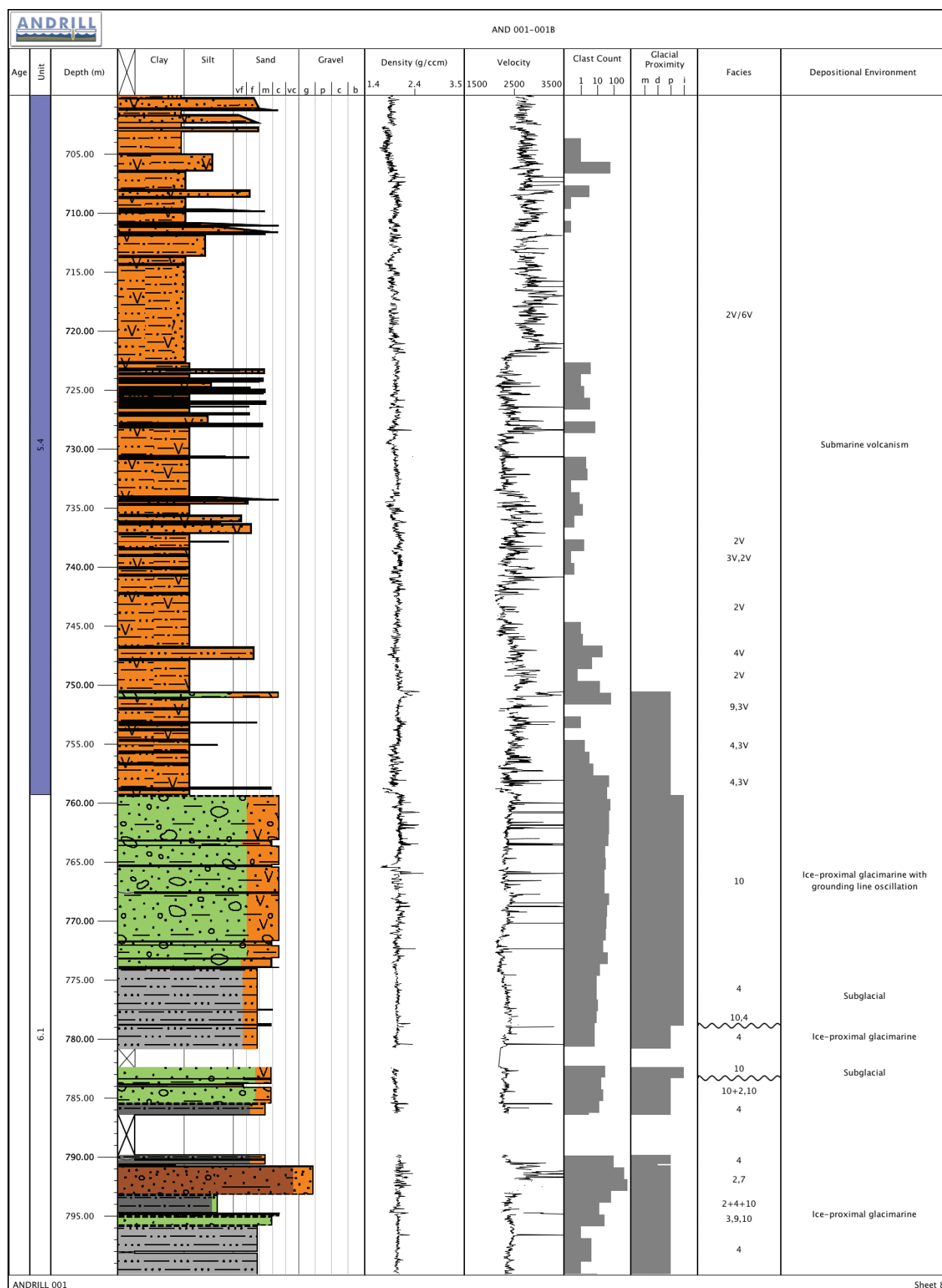


Fig. 1 – Continued.

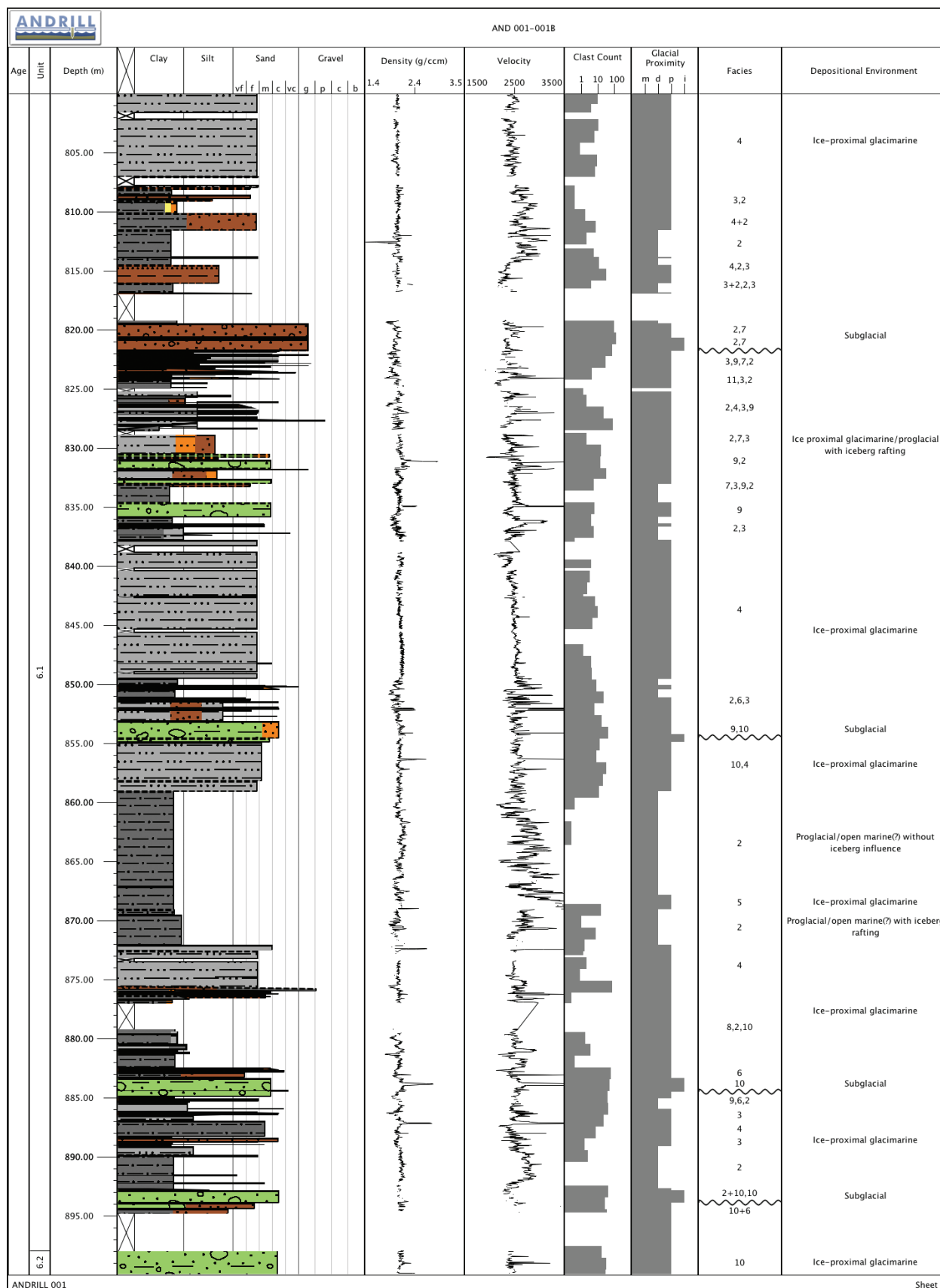


Fig. 1 – Continued.

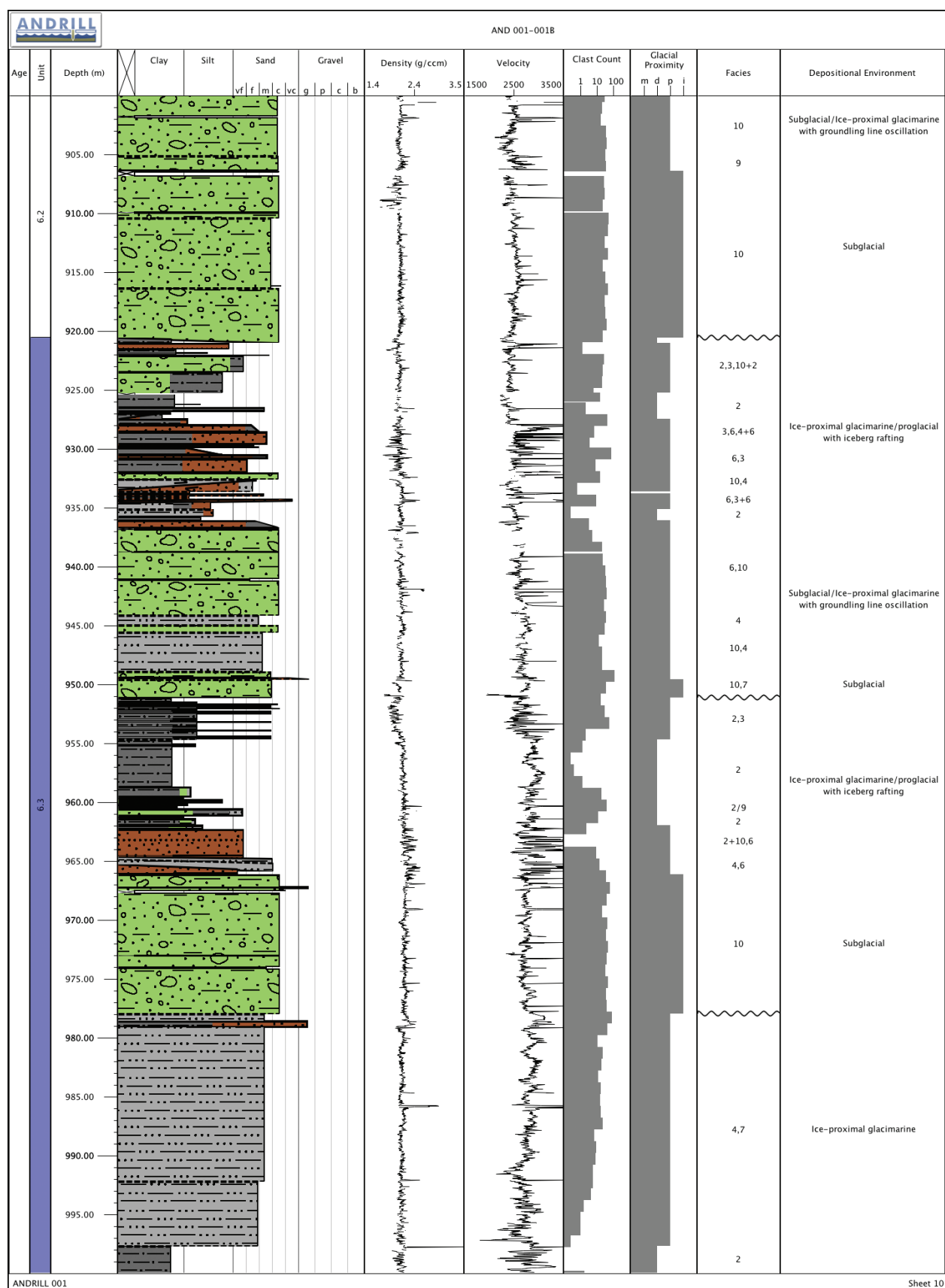


Fig. 1 – Continued.

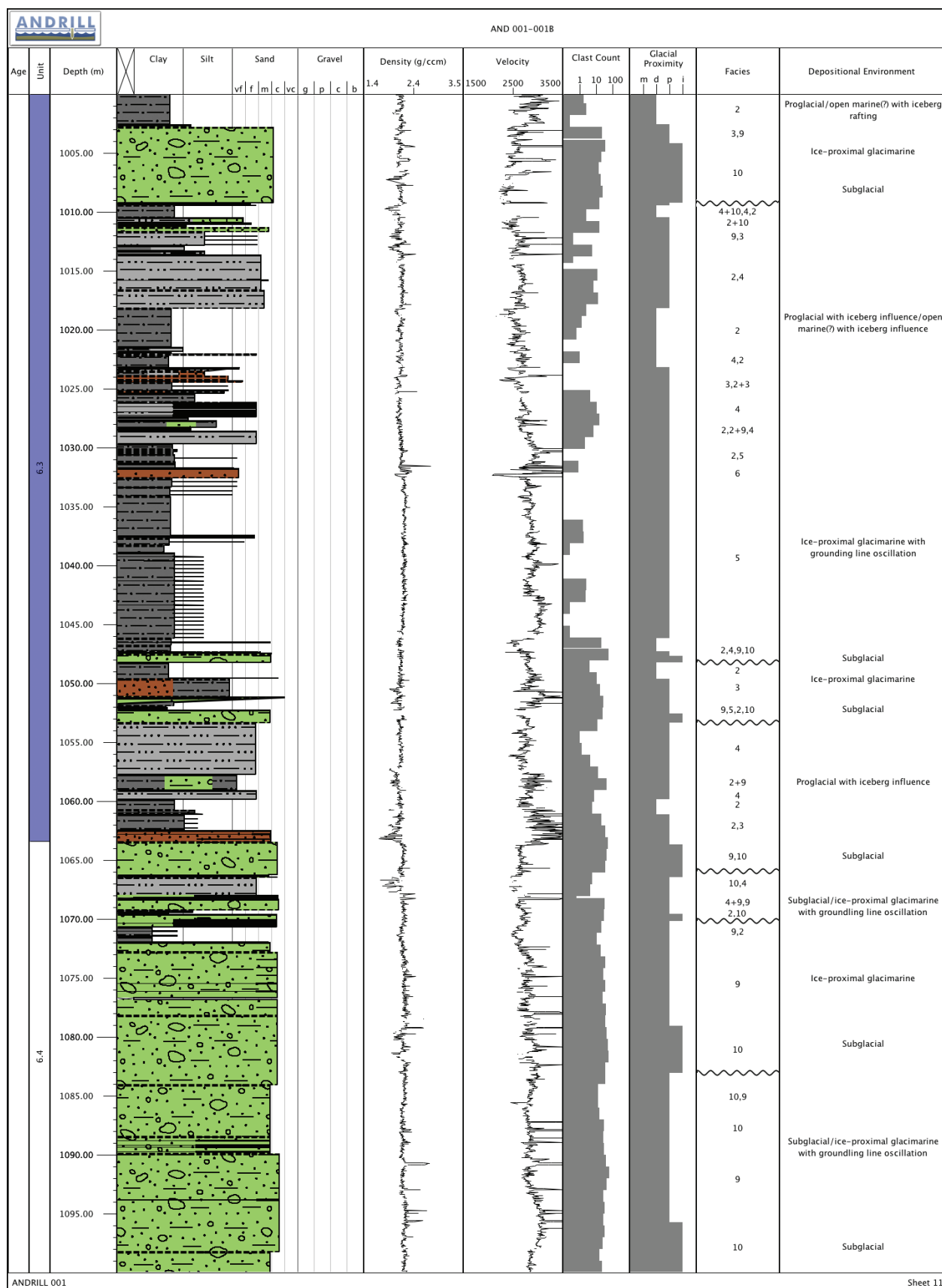


Fig. 1 – Continued.

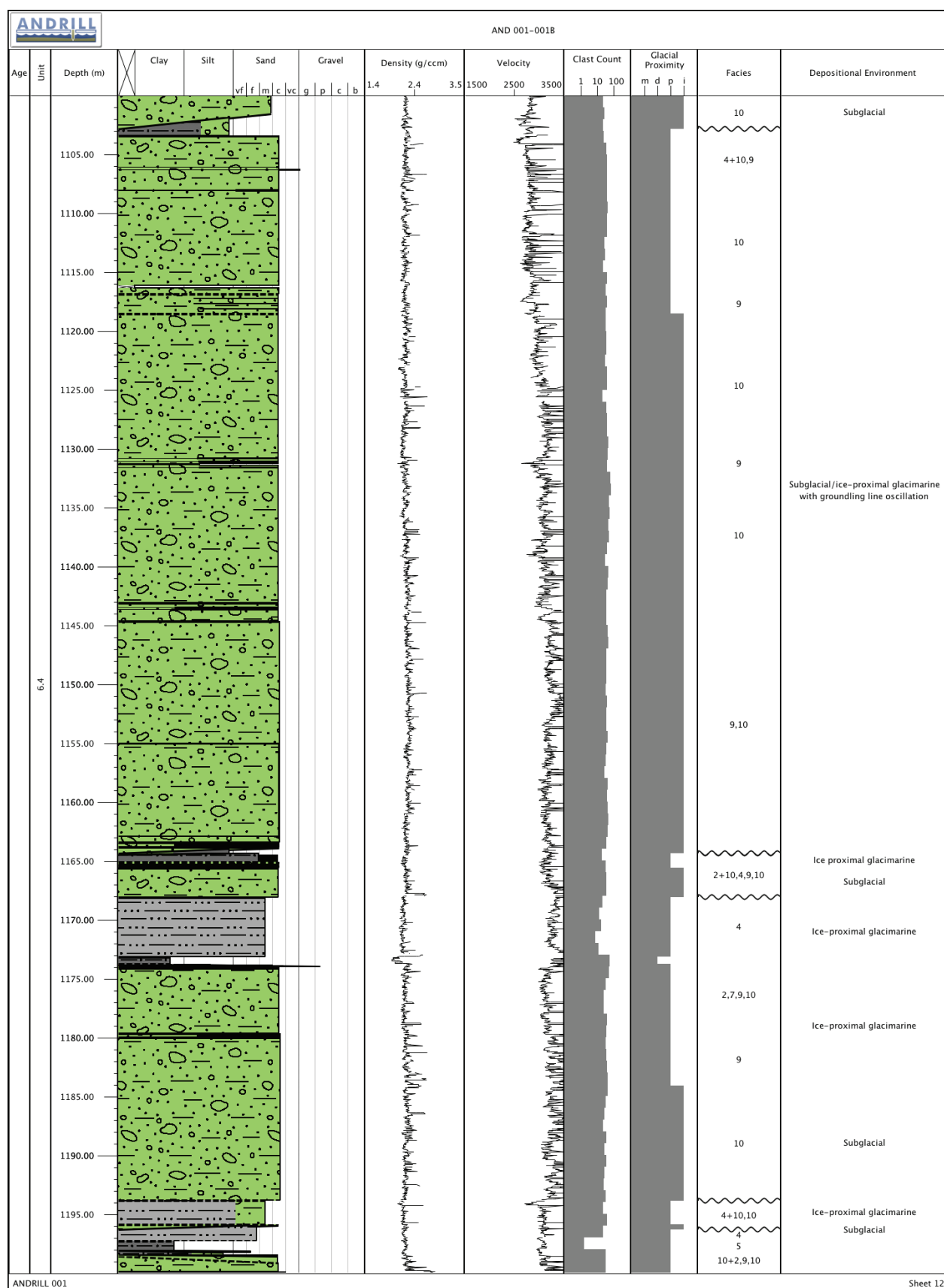


Fig. 1 – Continued.

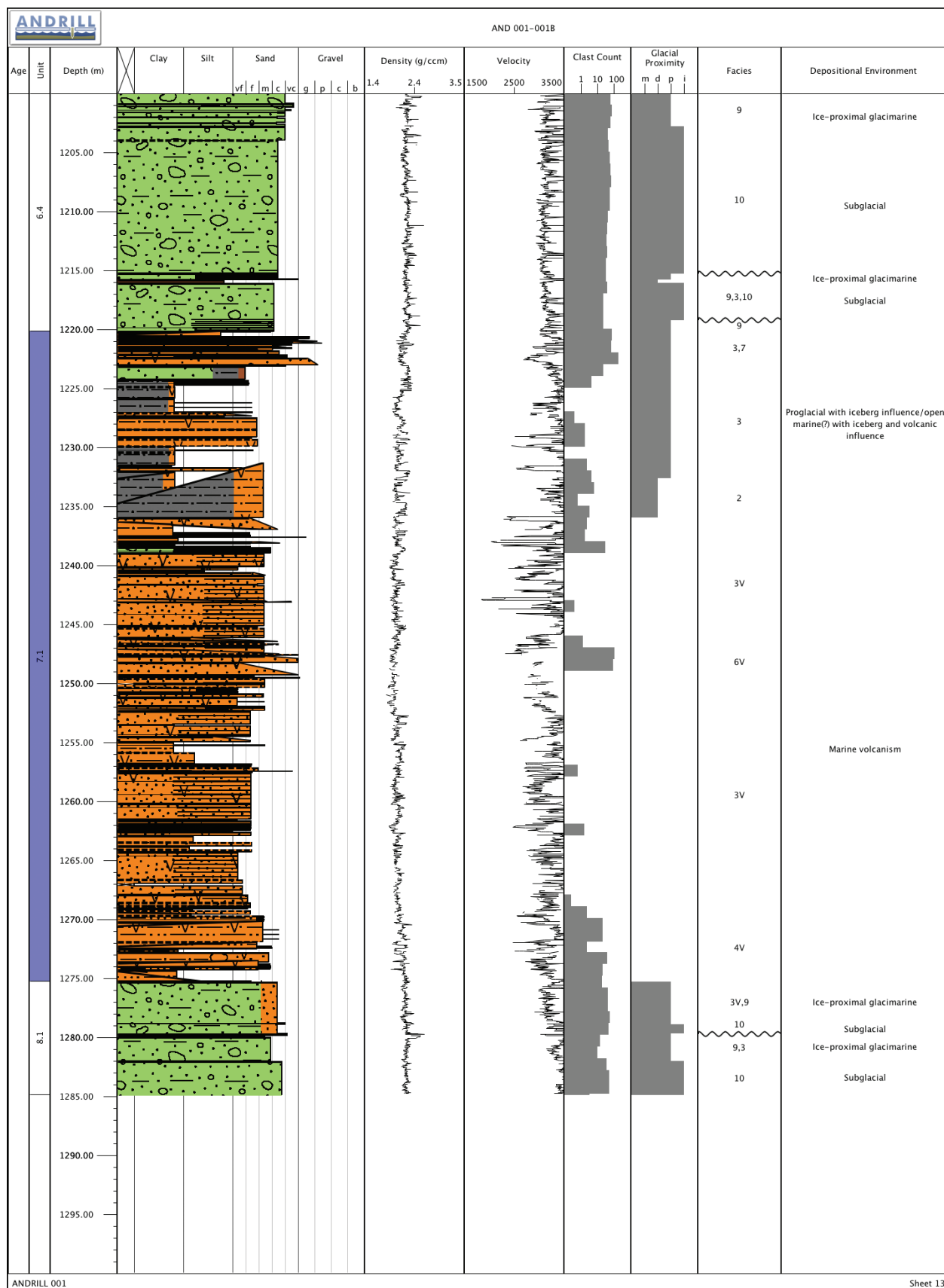


Fig. 1 – Continued.

Facies 4 (mudstone with dispersed or common clasts) is interpreted to record an environment similar to that of Facies 2, dominated by hemipelagic suspension settling but with increased clast rainout from floating ice. Rainout from icebergs cannot be distinguished from rainout beneath an ice shelf without additional study. Facies 5 (rhythmically interlaminated mudstone/siltstone/sandstone) is interpreted to have been deposited in a quiet-water setting by settling from meltwater plumes. The rhythmic nature of sedimentation may record interactions between the turbid plumes and tidal currents, whereas dropstones and poorly sorted sands record rainout from floating ice.

Facies 6 (sandstone) includes well-stratified sandstones and interbedded siltstones, usually with a strong volcanic component. Physical sedimentary structures and abundant fining-upward packages support the interpretation of Facies 6 as predominantly the deposits of turbidity currents, which originated on slopes composed of volcanic material. Deposits of other flow types (e.g. grain flows) may also be present in Facies 6. Facies 7 (conglomerate) is relatively uncommon in the core but is interpreted as the product of submarine sediment redeposition. Deformed mudstone intraclasts in some of these conglomerates suggest deposition and deformation by grounded ice. Facies 8 (breccia) is also interpreted as the product of sediment redeposition by mass flow; the dominance of volcanic clasts and/or mudstone intraclasts in Facies 8 suggests derivation of the mass flows from a volcanic source.

Facies 9 (stratified diamictite) is interpreted to record a range of depositional environments, depending on the associated facies for each occurrence: ice rafting or debris-flow deposition, rainout of basal glacial debris with reworking by marine glacial outwash, or deposition beneath grounded ice. Facies 10 (massive diamictite) is primarily attributed to subglacial deposition, although rainout from floating ice and deposition by mass flow are also possibilities.

Facies 11 (volcanic rocks and sediments) are interpreted as primary and near-primary volcanic deposits, including volcanic diamictites, lapilli tuffs, and a phonolitic lava flow. Although the diamictites and lapilli tuffs may have been reworked slightly by high-density mass flows and low-density mass flows, respectively, the extent of reworking for Facies 11 is interpreted to be significantly less than the extent of reworking recorded by volcanic-rich equivalents of the other facies.

In a preliminary sequence stratigraphic analysis, more than 50 unconformity-bounded glacial marine sequences have been recognised. Each sequence contains a consistent vertical association of facies, interpreted to represent successive glacial advances and retreats across the continental shelf. Sequences are defined on the basis of vertical stacking patterns of facies, and each has a Glacial Surface of Erosion (GSE) at its base. Three distinct stratigraphic-cycle

motifs have been recognised in the portions of the core that are not volcanically dominated; no cycle motifs have been identified in the volcanic successions. One sequence motif is dominated by diamictite, and is interpreted as a glacial advance-retreat cycle that was 'top-truncated' by erosion during the subsequent ice advance. The second sequence motif includes the most complete record of ice advance, retreat, and readvance; it begins with a basal diamictite (Facies 10) overlying a GSE, and grades upward through ice retreat facies representing grounding-line depocentres, ice-shelf, and iceberg zones (Facies 9 or 5), more distal glacial marine deposits (Facies 6, 3, 2), and finally into open-water diatomites (Facies 1). This portion of the motif records the transition from subglacial to open-water settings. The upper half of this motif contains a similarly ordered stratigraphy that records ice advance, culminating in a stratified diamictite (Facies 9) that is deformed immediately below the overlying GSE; this portion of the motif records the transition from open-water to ice-proximal settings. The third sequence motif is similar to the second motif, except that diatomite is absent and the upper portion of the cycle is dominated by mudstones. In addition, the upper ice-advance portion of the motif tends to be either absent, truncated or thinned. Because the third sequence motif is most common below 590 mbsf, it is unclear whether the absence of diatomite has a depositional or a diagenetic (diatomite conversion to opal C-T) cause. Further detailed study should help answer this question.

The two major diagenetic features observed during core description are carbonate cements and nodules and pyrite cements and nodules; minor features are a crystalline white non-carbonate material (zeolites?) and possible siderite. Carbonate cements occur as disseminated cement, millimetre-scale spherical nodules, centimetre-scale micritic beds or concretions, and vein/fracture fills. Diamictites and finer-grained terrigenous clastics generally contain more disseminated carbonate cement than diatomites and volcanic sediments, although the distribution of cement is highly heterogeneous in all lithologies. Millimetre-scale spherical carbonate-cemented nodules are only present in the volcanic sandstone at 141–145 mbsf. Micritic beds and centimetre-scale concretions are rare, but their host lithology most commonly is diatomite. Carbonate vein fills and fracture fills occur throughout the core, but are best developed below 600 mbsf, where they occur in a variety of forms.

Pyrite occurs as disseminated pyrite and pyritic grain coatings, concentrated pyrite cement, and pyrite nodules and concretions. All of these forms are rare to absent above ~400 mbsf but are common to abundant (and locally dominant) below that level; locally, the pyrite overprint is sufficiently concentrated to obscure sediment texture and stratification. The pyrite overprint generally is strongest in the volcanic sediments below 400 mbsf.

Deformational features include fractures, faults,

and convolute bedding, all of which are distributed irregularly through the core. Above ~650 mbsf, fractures generally are present in millimetre- to centimetre-spaced anastomosing networks, which produce colour mottling or a brecciated pattern in the core. Discrete single fractures are relatively rare above ~650 mbsf and are short and non-branching. Below ~650 mbsf, the fracture assemblage is more diverse, including anastomosing networks, discrete long and complex fracture systems, discrete long single fractures, and fractures emanating from larger clasts in the diamictites. The diversity of these fractures, as well as their cross-cutting relationships, indicates a complex multi-generational stress history in the region. Further study will work to distinguish tectonic from glaciotectonic contributions to this stress history.

Faulting generally is linked to the distribution of fracturing in the core. The most common fault style is conjugate fault sets that accompany the anastomosing fracture networks; low-angle thrust faults and low- to high-angle normal faults are also present. Low-angle thrust faulting is most evident near the bases of diamictites, where it is interpreted as evidence of subglacial shearing. Normal faults are distributed through much of the section above ~400 mbsf and below ~800 mbsf; shallower faults tend to be short, whereas deeper faults include both short and long faults.

A preliminary qualitative assessment indicates that soft-sediment deformation (as indicated by convolute bedding) is most abundant in intervals with at least one of the following three lithologies: diamictite, volcanicsandstone/siltstone, and stratified terrigenous mudstones/siltstones/sandstones. These lithologies generally are interpreted as forming in settings of rapid deposition and/or loading, which is consistent with the conditions needed for sediment destabilization. However, convolute bedding is not present in all occurrences of these three lithologies, suggesting that more detailed studies of the distribution and styles of soft-sediment deformation may be very helpful for refining depositional models and improving the palaeoenvironmental interpretations of this core.

EXPLANATORY NOTES

The objectives, roles, operations, and procedures of the ANDRILL McMurdo Ice Shelf (MIS) sedimentology/stratigraphy team were described in the *Scientific Logistics Implementation Plan for the ANDRILL McMurdo Ice Shelf Project* (SLIP; Naish et al. 2006). For the most part, actual operations and procedures followed the description given beforehand in the SLIP; however, some roles, operations, and procedures deviated from those described in the SLIP, and those changes are documented here.

Roles: Because the commitment to core description consumed all the efforts of the night-shift sedimentologists, the day-shift sedimentologists

assumed the primary role for the more integrative and interpretive tasks. These tasks included (1) defining and describing lithostratigraphic units (Lionel Carter and Greg Browne); (2) developing the lithofacies scheme (Rob McKay, Greg Browne, Ross Powell, Tim Naish, and Lionel Carter); (3) developing summary graphic logs (Rob McKay and Josh Reed); (4) developing general interpretations of glacial proximity and environments of deposition (Rob McKay and Greg Browne); and (5) developing a preliminary sequence stratigraphy (Greg Browne, Rob McKay, Tim Naish, and Ross Powell). After the core-description phase was completed, the night-shift sedimentologists contributed to these efforts by reviewing the existing classifications and interpretations and by providing additional descriptions, discussions, and interpretations. During the core-description phase, Vanessa Miller, ARISE (ANDRILL Research Immersion for Science Educators) participant, worked with the night shift sedimentologists. Her primary responsibility was the production of smear slides.

Procedures: The SLIP described a procedure that was planned to input core descriptions directly from the night-shift sedimentologists into PSICAT (Palaeontological Stratigraphic Interval Construction and Analysis Tool), bypassing the intermediate step of a description written on paper. This approach was used for the first week of core description, but it proved relatively inefficient for several reasons: (1) the PSICAT operator (Larry Krissek) was inexperienced and was still becoming familiar with the most efficient way to enter a description; (2) the core describers had difficulty ensuring that all parts of a description were included without the equivalent of a written checklist, as found on a core-description form; (3) the PSICAT operator had unused time when the core describers encountered an interval that required discussion before the description was finalized; (4) the core describers had unused time when a complicated interval was being entered into PSICAT; and (5) additional unused time was introduced because of the time lag between identifying the location for a smear slide and receiving information about the composition of that smear slide.

In order to improve the efficiency of the core-description process, our procedure was modified to include the intermediate step of a written description, which was then passed to Larry Krissek for entry into PSICAT. Although this modification introduced an additional step into the core-description process, it improved efficiency and core-description quality in several ways: (1) the work of the core describers (Ellen Cowan, Gavin Dunbar, and Thom Wilch) was decoupled from the data entry into PSICAT, so that these two steps could proceed independently; (2) the core describers were able to continue describing core during the ~1 hour that Krissek spent preparing the daily core presentation late in each shift; (3) the description sheet served as a checklist of important observations, so that the information for each interval was complete by the time Krissek began to enter it

into PSICAT; and (4) Krissek was better able to ensure consistency in interval descriptions as he entered them into PSICAT.

Classification schemes: The classification scheme for granular sediments that was presented in the SLIP was used successfully during core description, although the names given to volcanoclastic granular sediments were modified based on the terminology proposed by White & Houghton (2006). Rather than naming the volcanic-dominated sediments on the basis of grain size and mode of origin (*i.e.* volcanoclastic, pyroclastic, or autoclastic processes), the volcanic-dominated sediments were given a textural name based solely on grain size (*e.g.* claystone, siltstone, sandstone, conglomerate, or diamictite) preceded by the modifier 'volcanic'. Volcanic dominance of a specific interval was recognised by the abundance of volcanic glass or altered volcanic glass, pumice or pumiceous grains, or euhedral mineral grains.

In order to ensure consistency in the PSICAT graphic logs, a graphic lithology and a representative grain size were assigned to each subdivision within Moncrieff's (1989) classification scheme for poorly sorted terrigenous clastic sediments containing gravel. These assignments are summarised in table 1. Equivalent assignments were made for the classes of poorly sorted volcanic sediments containing gravel; the only difference is that the equivalent volcanic lithologies, rather than terrigenous clastic lithologies, were assigned.

LITHOSTRATIGRAPHY

The following is a lithostratigraphic summary of ANDRILL Core AND-1B. It is based on core descriptions by the ANDRILL sedimentology team. All depths are

recorded as metres below sea floor (mbsf) unless otherwise stated, and relate to the depths recorded while drilling.

The sedimentary sequence is shown graphically in figure 1; this sequence has been subdivided into lithostratigraphic units, which are also listed in figure 1. A summary table of the lithostratigraphic units also is included here as table 2. In this summary we have tried to establish an objective description of the rock units, and have subdivided the cored interval into eight lithostratigraphic units based on significant lithological changes observed downcore. Where appropriate, some of the units are subdivided into lithostratigraphic subunits (LSUs).

Lithostratigraphic Subunit 1.1

Muddy Diamictite with Mudstone and Sandstone; 0 to 82.74 mbsf (82.74 m thick)

LSU 1.1 is dominated by diamictite. It encompasses a suite of beds (3 to 26 m thick) of clast-poor to clast-rich, muddy diamict to diamictite, separated by thin (<3 m) sequences of interbedded mudstone, sandstone, and occasionally, conglomerate. The diamictites and their unconsolidated counterparts are typically massive but have localised zones of weak stratification defined by variations in clast concentration or preferentially oriented clasts. Better-defined stratification occurs near the upper parts of the diamictite and comprises thin beds of clast-rich diamictite or silty claystone to clayey siltstone. Diamictites are dark to very dark greenish grey, with a muddy to sandy matrix bearing rare amounts of brown volcanic glass, rare to trace occurrences of biosiliceous remains, and traces of foraminifers. Clasts are dispersed throughout and are dominated by three basic populations: (1) angular to

Tab. 1 - Lithologies and grain-size values used on the graphic logs to represent the sediment classes of Moncrieff (1989; poorly sorted terrigenous clastic sediments containing gravel). Equivalent volcanic lithologies and the same grain sizes were used to represent the classes of poorly sorted volcanic sediments containing gravel.

Name	Lithology	Grain Size Mark
Mud with dispersed clasts	Silt, siltstone, silty shale	Boundary fine/medium sand
Sandy mud with dispersed clasts	Shale, sandy or silty	Middle of medium sand range
Muddy sand with dispersed clasts	Sandstone, argillaceous	Boundary medium/coarse sand
Sand with dispersed clasts	Sandstone, massive	Coarse/vc sand (or above?)
Mud with common clasts	Silt, siltstone, silty shale	Middle of medium sand range
Clast-poor muddy diamict	Diamict or till	Boundary medium/coarse sand
Clast-poor sandy diamict	Diamict or till	Middle of coarse sand range
Sand with common clasts	Sandstone, massive	Coarse/vc sand (or above?)
Mud with abundant clasts	Silt, siltstone, silty shale	Boundary medium/coarse sand
Clast-rich muddy diamict	Diamict or till	Middle of coarse sand range
Clast-rich sandy diamict	Diamict or till	Boundary coarse/v coarse sand
Sand with abundant clasts	Sandstone, massive	Middle v coarse sand (or above?)
Muddy cgl/breccia	50% silt, siltst, silty shale; 50% gravel or cgl	Boundary coarse/v coarse sand
Sandy muddy cgl/breccia	50% shale, sandy or silty; 50% gravel or cgl	Middle of granule range (?)
Muddy sandy cgl/breccia	50% sandst, argillaceous; 50% gravel or cgl	Mid to upper granule (?)
Sandy cgl/breccia	50% sandst, massive; 50% gravel or cgl	Boundary vc sand/gravel (or larger)

"XX-bearing" => show 10%

"XX-rich" => show 30%

Tab. 2 - Summary of the lithostratigraphic units defined within AND-1B.

LSU	Depth - top	Depth - base	Unit Thickness	Lithology
1.1	0	82.74	82.74	Muddy diamictite with mudstone & sandstone
2.1	82.74	86.63	3.89	Claystone and volcanic ash/tuff
2.2	86.63	94.52	7.89	Mudstone-rich diatomaceous ooze
2.3	94.52	132.83	38.31	Diamictite, volcanic sandstone, & silty claystone
2.4	132.83	146.79	13.96	Volcanic sandstone, siltstone, and mudstone
3.1	146.79	169.4	22.61	Muddy diamictite with diatomite
3.2	169.4	181.93	12.53	Silty claystone & mudstone alternating with diatomite
3.3	181.93	292.66	110.73	Alternating diamictite & diatomite
3.4	292.66	347.19	54.53	Biosiliceous-bearing diamictite
3.5	347.19	363.37	16.18	Silty claystone, sandstone, & muddy diamictite
3.6	363.37	382.98	19.61	Biosiliceous-rich diatomite, mudstone, & diamictite
4.1	382.98	459.24	76.26	Diatomite
4.2	459.24	511.18	51.94	Diamictite, mudstone, and diatomite
4.3	511.18	575.12	63.94	Volcanic diamictite, mudstone, & diatomite
4.4	575.11	586.45	11.34	Volcanic diamictite, sandstone, & mudstone
5.1	586.45	646.49	60.04	Volcanic sandstone, mudstone, & diamictite
5.2	646.49	649.3	2.81	Phonolitic lava
5.3	649.3	688.92	39.62	Volcanic sandstone, mudstone, & diamictite
5.4	688.92	759.32	70.4	Volcanic mudstone, minor sandstone, & rare diamictite
6.1	759.32	897.95	138.63	Diamictite & mudstone with dispersed clasts
6.2	897.95	920.51	22.56	Muddy diamictite
6.3	920.51	1063.42	142.91	Mudstone-dominated, with diamictite & sandstone
6.4	1063.42	1220.15	156.73	Muddy diamictite with mudstone
7.1	1220.15	1275.24	55.09	Alternating volcanic sandstone & mudstone
8.1	1275.24	1284.87	9.63	Diamictite

subrounded mafic volcanics; (2) a subrounded to rounded heterolithic assemblage of granitoid, meta-sediment, felsic volcanics, and quartz; and (3) sedimentary intraclasts of mudstone and diamictite. Relative proportions of clast lithologies vary (for details, see Pompilio et al. this volume). In general, mafic volcanic clasts prevail in the upper diamict-diamictite (26.68 to 41.10 mbsf) whereas, apart from a brief increase in volcanic clasts centred on ~50.23 mbsf, the rest of LSU 1.1 is dominated by the heterolithic assemblage. Total numbers of clasts are also variable.

The thin sequences of interbedded sediment between the diamictites are composed mainly of mudstone that includes very dark greenish grey, clayey siltstone to silty claystone, or their unconsolidated counterparts, in the uppermost 40 m of the LSU. Muds are either massive or bioturbated but often have millimetre-scale laminae of sandstone. Dispersed clasts are well represented but are not ubiquitous. Other components are possible volcanic ash (25.65 to 26.28 mbsf), occasional trace amounts of biosiliceous remains, trace foraminifers, and at least one instance of mudstone intraclasts. The mudstones are interbedded with mainly volcanic sandstone that is especially well represented in the upper unit (<26.43 mbsf). Sandstones are typically fine- to medium-grained, with one bed reaching coarse grades. Basal contacts are either gradational or sharp, with the latter associated with fining-up sequences. Components include mafic volcanic rock

fragments, fresh glass, and feldspar. Muddy sandy conglomerate was identified near the base of two diamict layers. One conglomerate was disturbed by drilling, but the intact section has a diverse clast population of mafic volcanic, granitoid, metamorphic (including a single marble clast), and diamictite lithologies.

Lithostratigraphic Subunit 2.1

Claystone and Volcanic Ash/Tuff; 82.74 to 86.63 mbsf (3.89 m thick)

Lithostratigraphic unit 2 comprises a series of intercalated sandstones, mudstones, diatomites and diamictites, all with a variable volcanic content.

LSU 2.1 is characterised by its volcanic content, and comprises a succession of volcanic ash/lapilli beds and laminae that are interbedded with claystone and two sandstone beds. Where intact, the grey volcanic ash beds are 1 to 10 cm thick with sharp bases and normal grading from coarse to fine. At least one ash layer has a faulted base, and others are associated with soft-sediment deformation. A 0.6 m-thick bed of grey lapilli tuff is a compound feature of normally graded, coarse to fine ash beds that sometimes have scoured bases, cross stratification, and mud rip-up clasts (85.27 to 85.87 mbsf). Subrounded, dark volcanic lithic grains are abundant along with rare, rounded crystals. The matrix is predominantly angular, vesicular glass with silt-sized pumice and rare feldspar euhedral crystals. Two layers of vesiculated, dark grey lapilli tuff at 84.10 and 83.87 mbsf are well

indurated and may be cored clasts. The intervening beds of claystone are dark to very dark greenish grey, moderately bioturbated sediments with no (or trace amounts of) biosiliceous debris, rare to trace amounts of volcanic glass, rare limestones, and ash laminae. The remaining two lithologies are a bed of (1) volcanic pebbly sandstone with a matrix rich in vesiculated glass and trace amounts of biosiliceous remains, and (2) a bed of medium- to fine-grained sandstone with Bouma features that include (going upcore) a sharp base with load and flame structures, parallel laminae, cross laminae, and normal grading.

Lithostratigraphic Subunit 2.2

Mudstone-rich Diatomaceous Ooze to Diatom-rich Silty Claystone; 86.63 to 94.52 mbsf (7.89 m thick)

LSU 2.2 is mainly a diatomaceous ooze. It begins as a diatom-rich mudstone that grades downcore into a very dark greenish grey, silty claystone-rich diatomaceous ooze. The first biogenic deposit detected is weakly bioturbated and stratified, the latter including a small percentage of sand and granules. Clasts of mainly granule to small-pebble grade are generally dispersed throughout and have mafic volcanic, felsic volcanic, and metasedimentary affinities. Smear slides contain rounded grains of volcanic glass. At 89.39 mbsf, the diatom ooze is replaced abruptly by very dark greenish grey, diatom-rich, volcanic ash-bearing silty claystone that resembles the overlying sediments apart from reduced biosilica and increased volcanic components. Biosilica continues to decrease downcore to 25%, to render the sediment diatom-bearing. Clasts are dispersed throughout and are mainly granule size. The base of the unit becomes a diatom-rich silty claystone, which is physically mixed with clayey volcanic sand and clayey siltstone to silty claystone. Sediments are locally contorted into recumbent folds, and some display normally graded successions with rip-up clasts. Of note is calcareous shelly debris (90.80 to 91.22 mbsf), including bryozoan, molluscan, and foraminiferal remains. LSU 2.2 rests unconformably on the next subunit.

Lithostratigraphic Subunit 2.3:

Interbedded Diamictite, Volcanic Sandstone and Silty Claystone; 94.52 to 132.83 mbsf (38.31 m thick)

Silty claystone, volcanic sandstone, and diamictite constitute LSU 2.3. Also of note is an isolated zone of biosiliceous ooze. Very dark greenish grey silty claystone, locally coarsening to mudstone, are the fine-grained lithologies. For the most part these lithologies are bioturbated. Nevertheless, the silty claystone has weak stratification resulting from either differing concentrations of sand or colour variations. The exceptions are several zones, located between 132.07 and 132.28 mbsf, with horizontal to subhorizontal laminae that are well defined by black and dark greenish grey colour alternations. The black colouration (and indeed the black colour through much of the core) is due to pyrite and does not appear to be related to original deposition (for

details, see 'Diagenesis' section below). Locally, the silty claystone/mudstone beds have undergone soft-sediment deformation especially near the diamictites. Dispersed clasts tend to be more abundant near the tops of the fine sediment beds, where there is also the least amount of biosiliceous component. While the trend is irregular and is interrupted midway through LSU 2.3 by an ooze, the biosiliceous content of the silty claystone/mudstone beds tends to increase downcore from trace amounts to a few percent. The biosiliceous ooze (117.16 to 117.74 mbsf) is very dark greenish grey and moderately bioturbated, although it still retains remnants of colour-defined laminae. Both upper and lower parts of the ooze pass into biosiliceous-bearing clayey siltstone.

Very dark grey to black, fine to medium volcanic sandstones, plus one interbed of volcanic breccia, are prominent constituents of LSU 2.3. Beds range from thick (up to at least 1.3 m) and unstratified to sharp-based ones exhibiting some combination of parallel lamination, ripple cross-bedding, and mud rip-up clasts. Vesicular glass is a common component.

The thickest beds (8.72 m maximum) are dark greenish grey, clast-rich diamictites that range locally to clast-poor diamictite. Stratification is generally absent, but it does occur as concentrations of coarser clasts and laminae of dark grey claystone. However, the latter could also be drilling-mud contaminant. Clasts are mainly granule to small-pebble grade, and encompass diamictites, mafic volcanics, metasediments, granitoids, and sandstone.

Lithostratigraphic Subunit 2.4

Volcanic Sandstone, Volcanic Siltstone, and Volcanic Mudstone; 132.83 to 146.79 mbsf (13.96 m thick)

LSU 2.4 is marked by its volcanic content and commences as a stack of fine sandstones with sharp bases and normal grading that can pass to siltstone or silty claystone. The beds consist of volcanic sandy mudstone and siltstone containing granule- to small pebble-sized black mafic clasts and an abundance of volcanic glass. The remainder of the unit is a succession of black, very fine to medium volcanic sandstones that include thick (> ~15 cm), massive to fining-up beds interspersed with stacks of thin (0.3 to 3 cm) layers that are predominantly normally graded. Again the black colour appears to be related to the presence of pyrite. Both thick and thin beds usually have sharp bases, parallel lamination, and occasional ripple-drift bedding. Soft-sediment deformation is common and manifested by convoluted laminae and other deformed layering. Angular vesiculated volcanic glass is abundant, whereas biosiliceous remains were not detected in smear slides.

Lithostratigraphic Subunit 3.1

Clast-rich to Clast-poor Muddy Diamictite Alternating with Diatomite; 146.79 to 169.40 mbsf (22.61 m thick)

Lithostratigraphic Unit 3 still comprises a range of sediment types, but is distinguished on the basis of a change to biosiliceous- or diatom-bearing lithologies.

Lithostratigraphic Unit 3 also marks a major change in lithology with the onset of major oscillations between diamictite and diatomite.

LSU 3.1 includes two diamictite/diatomite cycles. The terrigenous deposits are mainly greenish black, clast-rich muddy diamictites that locally grade into clast-poor muddy diamictites. Stratification occurs mainly near the top of the younger and thicker diamictite (146.79 to 150.73 mbsf) and is confined to colour changes in the matrix or increased clast content. Clasts are mainly granules but can reach small pebble size. They are initially dominated by mafic volcanics, but are superseded downcore by more varied lithologies. The matrix has; (1) fresh volcanic glass which is found proximal to volcanic-dominant LSU 2.4, and (2) a few percent of biosiliceous remains, especially near the top and bottom of individual diamictite beds.

Separating the main diamictite beds are dark grey to dark greenish grey to olive grey diatomite. Because of a core gap at 159.34 to 160.19 mbsf, the transition from diamictite to diatomite is seen only in one cycle and tends to be gradational with decreasing amounts of mud upcore. In contrast, the upcore transition from diatomite to diamictite tends to be more abrupt, although it is still heralded by increasing amounts of mud. Importantly, this upper transition is characterised by physical mixing of the diamictite and diatomite lithologies via soft-sediment deformation and pervasive fracturing/faulting. The diatomite itself displays weak colour banding at the centimetre scale, but this is disrupted locally by fracturing/faulting and moderate to heavy bioturbation. Dispersed coarse sand, granules and small pebbles are rare to a few percent, and may be concentrated locally into lenses or laminae.

Lithostratigraphic Subunit 3.2

Silty Claystone and Mudstone Alternating with Diatomite; 169.40 to 181.93 mbsf (12.53 m thick)

LSU 3.2 is a succession of mudstone and silty claystone that is interrupted by diatomite. The subunit commences as a greenish black mudstone with dispersed clasts. The black colour appears to be caused by pyrite. Any primary stratification is obscured by a combination of bioturbation, soft-sediment deformation and extensive fracturing/faulting. The mudstone grades down to a very dark grey, biosiliceous-bearing to biosiliceous-rich silty claystone with rare limestones and the same obscured stratification as noted previously. A sharp contact marks the appearance of diatomite (174.50 to 178.27 mbsf). The section is interrupted from 178.60 to 178.73 mbsf by a faulted and brecciated wedge of biosiliceous-bearing silty claystone and volcanic sandstone. Also of note is the appearance of a diamictite component within the diatomite immediately above the wedge (178.27 to 178.60 mbsf). In general terms, the diatomite above the wedge is dark grey, whereas below it is dark greenish grey, suggesting that they are discontinuous. Both sections have

suffered some combination of biological and physical disruption similar to that encountered in the overlying beds. Outside the diamictite-bearing diatomite, which has granule-coarse sand clasts of mafic volcanic and metasedimentary origin, the rest of the diatomite contains dispersed coarse sand. Near its base, the diatomite becomes silty clay bearing, before terminating at an irregular sharp contact with an underlying black, silty claystone. This basal deposit contains dispersed sand grains and exhibits weak stratification that is locally obscured by faulting.

Lithostratigraphic Subunit 3.3

Alternating Diamictite and Diatomite; 181.93 to 292.66 mbsf (110.73 m thick)

LSU 3.3 is a 110.73 m-thick package of alternating beds of diamictite and diatomite. Diamictite beds range from 1.49 to 27.3 m thick whereas diatomites have a more restricted range of 1.94 to 13.03 m thick. Five major diamictite/diatomite couples are present, and have variable boundaries. Passing upcore from diatomite to diamictite, boundaries are abrupt or gradational. Whatever the transition, these boundaries are disrupted by either soft-sediment deformation or extensive fracturing/fracturing or by both these processes. Upcore changes from diamictite to diatomite tend to be gradational and are either deformed or intact.

The diamictite beds are mainly clast-poor but contain clast-rich intervals at either the bed top or bottom. Stratification tends to be weak, and when present, is found near the tops or bottoms of beds. A general paucity of primary layering may reflect masking by brittle and soft-sediment deformation, which at times is sufficiently pervasive to give the rock a brecciated appearance. Nevertheless, thick diamictite beds are interrupted by thin beds of sandy mudstone, and rarely, silty sandstone with or without dispersed clasts. These interbeds are lithologically very similar to the diamictite matrix. Clasts are predominantly angular to rounded granules with small pebbles occurring locally. A range of compositions is present, but mafic volcanics tend to dominate. A small biosiliceous component is found in the youngest and oldest diamictites, and occurs near transitions with diatomite. Also of note are millimetre-sized fragments of biogenic carbonate, which are irregularly scattered through the diamictite succession.

Diatomite is mainly olive grey but can become dark olive grey or dark greenish grey approaching the contacts with diamictites. Yellow laminae appear sporadically and in some cases represent near-monospecific diatom assemblages. Fracturing and/or faulting may be sufficiently pervasive to brecciate the rock. Fractures are commonly filled with calcitic cement. Diatomite contains varying amounts of sand and, less commonly, granules and pebbles that tend to be more common in the basal sections overlying diamictite. Grains are usually dispersed but are locally concentrated into lenses up to 1 cm thick and layers of a single grain thickness. Where preserved,

bioturbation is evident as millimetre-scale 'speckled' structures resembling *Chondrites* or *Helminthopsis*. Burrows are sometimes accompanied by diffuse pyrite staining. Between 292.04 and 292.38 mbsf, the diatomite is carbonate cemented.

While changes from diamictite to diatomite and vice versa are usually short and involve only those lithologies, two transitions encompass other sedimentary types.

- 224.54 to 224.93 mbsf. The upcore change from diamictite to diatomite incorporates a stack of very dark grey to very dark green fine sandstones with sharp bases, millimetre-scale parallel laminations, and normal grading up to a silty claystone. The stack is capped by 0.04 m of grey, crystalline carbonate which, from its slow reaction with acid, may be dolomitic.
- 258.53 to 260.86 mbsf. The upcore transition from diamictite to diatomite comprises massive sandstone and silty claystone with sandstone laminae, the thicker layers usually exhibiting grading and laminations. Locally, the sandstone and claystone are physically intermixed.

Lithostratigraphic Subunit 3.4

Biosiliceous-Bearing Diamictite; 292.66 to 347.19 mbsf (54.53 m thick)

Beginning as a diatomite-bearing, silty claystone and sandy mudstone, LSU 3.4 rapidly becomes a clast-rich muddy diamictite that grades to a clast-poor equivalent. At 306.75 mbsf, the sediment becomes a biosiliceous-bearing clast-poor muddy diamictite, this biosiliceous content persisting for the next 40.44 m. For much of its length, the diamictite is clast-poor to the extent that it temporarily reverts to a biosiliceous-bearing sandy mudstone or varieties thereof (316.20 to 326.46 mbsf), which are found as massive beds and in 5–20 cm-thick interbeds within a diamictite section. The sandy mudstone is essentially diamictite matrix. However, some clast-rich beds are also evident. Clasts are predominantly granule grade with minor pebbles. The dominant clasts are angular to subrounded mafic volcanics, although other lithologies such as meta-sediments are also present. Trace occurrences of millimetre-sized carbonate shell fragments appear throughout the sub-unit. Volcanic glass is found in sufficient amounts at 295.46 to 296.45 mbsf, and at 319.54 to 326.46 mbsf, to reclassify the sediment as biosiliceous-bearing, volcanic- glass-bearing, clast-poor muddy diamictite. Where noted, the glass consists of pale brown, subrounded grains up to fine sand size.

Lithostratigraphic Subunit 3.5

Silty Claystone, Sandstone and Clast-poor Muddy Diamictite; 347.19 to 363.37 mbsf (16.18 m thick)

LSU 3.5 initially comprises a very dark grey, silty claystone with parallel, colour-defined laminae. These layers have survived despite pervasive fracturing. The claystone is superseded downcore by beds of black, fine- to medium-grained sandstone with parallel laminae and, in the case of one bed, normal grading.

The interval 348.12 to 352.51 mbsf includes one or more mass-flow deposits involving physical mixing of the following lithologies: (i) very dark grey silty claystone; (ii) black fine sandstone; (iii) very dark grey clast-rich sandy diamictite; (iv) mudstone with clasts; and (v) interstratified mudstone, sandstone, and diamict. The dark colouration is due to pervasive pyrite diagenesis. Underlying the mass-flow deposit(s) is a succession of sandstone interbeds, mudstone, biosiliceous-bearing mudstone, and thin beds (<0.40 cm) of clast-poor muddy diamictite. The fine- to medium-sandstone beds contain parallel laminae, occasional ripple-drift laminae, and rip-up clasts; these beds tend to decrease in thickness downcore. They are eventually reduced to isolated centimetre-thick beds; the last bed rests directly on the diamictite of the next subunit.

Lithostratigraphic Subunit 3.6

Biosiliceous-rich Diamictite, Biosiliceous-rich Sandy Mudstone and Intermixed Diamictite; 363.37 to 382.98 mbsf (19.61 m thick)

LSU 3.6 consists of three clast-poor muddy diamictites that are interbedded with biosiliceous-rich sandy mudstones containing dispersed clasts. The diamictites are separated by zones of physical intermixing characterised by oblique faulting and soft-sediment deformation. These intermixed zones range in thickness from 0.24 to 0.80 m. Diamictites are between 0.96 and 2.0 m in thickness, and are all biosiliceous-rich with predominantly granule- to pebble-grade clasts. All diamictites display local stratification defined by changes in grain size, matrix colour, or clast abundance. Clasts are mostly mafic volcanics, although a range of lithologies is present. The middle diamictite (370.38 to 372.38 mbsf) is interbedded with centimetre to decimetre-scale sandy mudstone. The sandy mudstone contains dispersed clasts of variable lithologies, although these are dominated by volcanics. The lowermost sandy mudstone (376.27 to 377.53 mbsf) appears to be physically intermixed with diatomite and diamictite, and is underlain by a series of intermixed silty claystone-bearing, diamictite-bearing diatomite.

Lithostratigraphic Subunit 4.1

Diatomite; 382.98 to 459.24 mbsf (76.26 m thick)

Lithostratigraphic Unit 4 is defined on the basis of its high diatomite content, especially in the upper part of the unit.

LSU 4.1 is a 76.26 m-thick unit of almost continuous diatomite. The uppermost 15 m are laminated at the millimetre to centimetre scale, although this can be obscured by millimetre- to centimetre-spaced subhorizontal and oblique faults. Laminations are generally defined by changes in colour. However, scattered throughout the diatomite are two distinct laminae types: (1) well-sorted fine sand, generally in laminae <5 mm; and (2) medium to coarse sand, granules, and rare pebbles in laminae 5–10 mm thick. Lonestones increase in abundance

below 389.66 mbsf, and pebbles include diamictite intraclasts and mafic volcanics. Below ~398 mbsf, the abundance of diamictite limestones decreases, whereas bioturbation increases significantly and persists throughout most of the subunit. Between 401.12 and 416.55 mbsf, there is an increase in terrigenous input and the unit alternates between 'pure' diatomite and sand- or silt-bearing diatomite, with occasional, 5 to 46 cm-thick interbeds, of fine sand. A distinctive zone of pervasive bioturbation at 419.55 to 445.55 mbsf has a 'speckled' appearance similar to *Helminthopsis*. Below 425.59 mbsf, the diatomite has undergone carbonate cementation in patches up to 7 cm thick. Towards the base of LSU 4.1, there are two brecciated zones (438.73 to 440.12 mbsf and 454.56 to 455.16 mbsf) with three components in varying proportions: (1) greenish grey muddy matrix of diatomite; (2) black volcanic sand; and (3) gravel-sized clasts. The randomly distributed clasts are angular to rounded and are predominantly mixed volcanics, although metasedimentary, diamictite, and sandstone clasts are also present. The lower 4.08 m of this unit is characterised by a zone of millimetre to centimetre-scale laminations that are obscured by bioturbation. Several trace fossils are present, including centimetre-scale horizontal burrows, centimetre-scale horizontal burrows with complex fill (*Zoophycos?*), and millimetre-scale ovoid, simple horizontal burrows. The contact with the underlying subunits is gradational despite a marked change in lithology over a short interval, and neither brittle nor soft-sediment deformations were recorded.

Lithostratigraphic Subunit 4.2

Diamictite, Mudstone and Diatomite; 459.24 to 511.18 mbsf (51.94 m thick)

LSU 4.2 is a diamictite-diatomite couplet with an intervening sequence of laminated to bedded silty claystone and silty claystone. The subunit commences as a short interval of volcanic-rich, muddy diamictite composed of clast-poor and clast-rich types, where stratification is defined by variations in granule to small pebble concentration. Further downcore (459.62 to 461.56 mbsf), the dominant lithology is dark greenish grey, silty claystone that displays weak, colour-defined stratification despite a moderate degree of bioturbation. This fine-grained rock also has (1) 1 to 4 cm-thick interbeds of muddy diamictite, which make up ~20% of the interval, and (2) single-grain to 5 mm-thick laminae of sandstone that are disrupted by bioturbation and soft-sediment deformation, which make up ~2% of the interval. The claystone rests with a sharp contact on very dark grey, muddy diamictite containing interbeds of very dark grey mudstone (461.56 to 482.70 mbsf). In its upper reaches, the diamictite has weak stratification that is defined by colour, clast size, or clast concentration. It also appears to be weakly bioturbated.

However, below 469.82 mbsf, any bedding or bioturbation is at least partially obscured by extensive fracturing and faulting. Above 473.39 mbsf, the

diamictites are clast-rich, and below this level, clast-poor. Clasts are mainly granule- to small-pebble grade and include a heterolithic assemblage that is usually dominated by mafic volcanics, although mudstone grains may prevail locally (462.54 mbsf). The beds of very dark greenish grey mudstone within the diamictite have weak stratification, which below 468.49 mbsf is masked by faulting and fracturing. Clasts are dispersed through the fine sediment and are mainly mudstone intraclasts and mafic volcanics. In the vicinity of a diamictite, the mudstone may be physically intermixed with the diamictite via brittle or soft-sediment deformation.

Much of the diatomite interval (503.42 to 510.58 mbsf) has a small quantity of mud and, in one instance, volcanic sand. These muddy and/or sandy diatomites are dark olive grey to very dark greenish grey to black. Pyrite diagenesis appears to have produced the dark colour. These colour differences help define laminae, sections of which may be deformed or overprinted by bioturbation structures. Overall, bioturbation is moderate. Only between 504.63 to 505.83 mbsf is the diatomite, now olive grey, considered to be nearly 'pure'. Terrigenous sand is dispersed throughout the interval, and may be concentrated into laminae and lenses (e.g. 504.11 to 504.63 mbsf). The diatomite grades down into a weakly stratified, biosiliceous-bearing silty claystone (510.58 to 511.56 mbsf) with slight to moderate bioturbation. Stratification is defined by millimetre-scale dark banding.

Separating the diamictite and diatomite is an interval (482.70 to 503.42) of predominantly silty claystone that may locally coarsen to clayey siltstone and siltstone. The interval is interrupted by (1) a short (<1 m) stack of three fine-grained volcanic sandstones with sharp bases and normal grading and (2) a thin (<1 m) diamictite. The fine-grained lithologies are dark greenish grey to black with strong to weak horizontal stratification at the centimetre-scale. These layers may result from differences in colour or grain size or both. Siltstone laminae with sharp bases and normal grading occur in the more silty beds, whereas silty claystone beds have weak, colour-defined laminae. Scattered pyrite nodules and hard, non-calcareous cemented zones further characterise the latter beds. Bioturbation is variable and ranges from light to heavy to 'unidentified', with the latter descriptor reflecting potential masking by brittle deformation and/or cementation. Transitions into the underlying diatomites are gradational and intact whereas transitions into overlying diamictites are abrupt and usually marked by faulting and fracturing of the claystone.

Lithostratigraphic Subunit 4.3

Volcanic-rich to Volcanic-bearing Diamictite, Mudstone and Diatomite; 511.18 to 575.12 mbsf (63.94 m thick)

LSU 4.3 is a mixed diamictite-diatomite dominated succession with relatively thin intervening mudstone interbeds. LSU 4.3 is grossly similar to the overlying

LSU 4.2, and is differentiated by the presence of variable proportions (*i.e.* >10%) of volcanic sand to coarse pebble material. The relative abundance of this volcanic material increases toward the base of the LSU, to the extent that the rock becomes very dark-coloured. Lithic material comprises volcanic as well as quartzose-feldspathic grains/clasts, typically pyrite coated, with considerable dark-coloured diagenetic carbonate. Fractures (both drilling- and geologically induced) appear to be more common in this LSU.

The top of LSU 4.3 is a 3 cm-thick volcanic glass-bearing sandy diamictite at 511.18 to 511.21 mbsf, the first unit with an appreciable (*i.e.* >10%) volcanic component, that passes downhole into an intercalated diamictite and mudstone with dispersed pebble-clast interval from 511.56 to 526.20 mbsf. The diamictite beds are typically very dark green, mud-rich, and unstratified, with granule- to small-pebble size mafic clasts as well as volcanic glass. They form bedded intervals up to 3 m thick. The diamictites are intercalated with thinner mudstone beds that contain dispersed clasts. These mudstones are bioturbated silty very dark grey claystones, with either massive or with weak horizontal stratification defined by slight colour variations. Typically they form beds up to 1.5 m thick. Rare dark grey, coarse-grained sandstone beds a few centimetres thick also occur through this interval. A 13.5 m-thick interval from 526.20 to 539.70 mbsf consists of a black to very dark grey, volcanic clast-rich, weakly to well-stratified muddy diamictite, with clasts up to 4 cm diameter. Carbonate-filled fractures are common through this interval.

The 11.08 m-thick interval from 539.70 to 550.78 mbsf is a mudstone-rich succession, and comprises very dark grey, non-stratified to weakly stratified mudstone with dispersed clasts. Stratification is marked by centimetre-thick concentrations of medium to coarse-grained sand. Clasts are angular to rounded granule to pebble sized with a range of compositions, though glassy mafic volcanic clasts predominate. Faults and fractures are common in this interval as are fractures, and many of the fractures are associated with pyrite cement.

A thin pebble band at 550.78 mbsf marks the transition into the underlying diatomite interval to 556.90 mbsf. This lithology is a very dark grey to black, silt-rich diatomite, massive to horizontally laminated and intensely bioturbated by *Chondrites?* and *Helminthopsis?* burrows. The lower half of this interval contains more clayey siltstone and lesser proportions of volcanic glass fragments and is more greenish grey in colour.

The interval from 556.90 to 565.48 mbsf comprises two diamictites interbedded with mudstone. The diamictites are each ~2 m thick, and comprise a dark greenish grey volcanic-bearing, clast-poor muddy diamictite, with clasts dominated by mafic material. The intercalated mudstone through this interval comprises two beds of very dark green-grey, sandy mudstone with dispersed clasts, each bed ~2 m thick. The clasts are dominated by volcanic granules, with metasedimentary clasts present.

Diatomite returns from 565.48 to 575.11 mbsf, the lithology comprising an olive grey to dark olive grey, bioturbated sand-rich diatomite with dispersed clasts.

Lithostratigraphic Subunit 4.4

Volcanic-rich Diatomite, Volcanic Sandstone, and Mudstone; 575.11 to 586.45 mbsf (11.34 mbsf)

LSU 4.4 is dominated by diatomite-rich sediments with less abundant intercalated volcanic sandstone and mudstone. LSU 4.4 is differentiated on the basis of its volcanic-rich nature (a larger percentage than LSU 4.3) which is reflected in its dark colour, the presence of volcanic-rich sandstones, as well as the presence of diatomite. Individual diatomite beds are up to 2 m thick and comprise olive grey to very dark grey, bioturbated sediments that are volcanic glass-bearing, with variable proportions of black sand and granules. The sand and granules are generally dispersed through the bed or may locally be concentrated into diffuse millimetre- to centimetre-thick layers. Weak horizontal stratification is typical and is defined by changes in colour or by grain size. Pyrite staining and bioturbation are common.

The intercalated sandstone consists of centimetre-thick dark greenish grey, medium- to coarse-grained, planar to ripple-laminated volcanic sandstone with both scoriaceous and mafic grains. Beds may be normally graded. Associated siltstones are less abundant (one bed occurring between 581.88 and 582.90 mbsf). The mudstone is a dark olive grey to very dark greenish grey volcanic sandy mudstone, bearing dispersed granules and rare pebbles.

A disrupted interval occurs between 584.6 and 584.85 mbsf.

Lithostratigraphic Subunit 5.1

Volcanic and Volcanic-rich Sandstone, Volcanic Mudstone and Volcanic Clast-Rich Diamictite; 586.45 to 646.49 mbsf (60.04 m thick)

Lithostratigraphic unit 5 is differentiated on the basis of its high volcanic content, lack of diatomite, and varied range of siliciclastic sediments.

LSU 5.1 is differentiated on the basis of its high volcanic content, which is reflected in its dark colour (due to the presence of pyrite), but it differs from the overlying unit in lacking diatomite. It is dominated by sandstone (many with granule to pebble clasts) and interbedded mudstone in variable proportions as well as lesser amounts of diamictite. The lower boundary of the LSU is marked by a 3 m-thick lava.

Volcanic and volcanic-rich sandstones are black in colour, and form beds up to 1.5 m thick. Normal grading is common. Bed bases are usually sharp and erosional; tops are either sharp and planar or gradational. The sediments are fine to very fine-grained, and all appear to be volcanic and/or with pyrite coating. Beds are either massive or planar laminated. Ripple lamination occurs but is rare. Beds contain scoriaceous, pumiceous, mafic volcanic and siltstone clasts, which are often found scattered throughout the beds.

Volcanic sandy mudstones often occur intercalated with the sandstone. They form beds up to 1 m thick and are dark olive grey to very dark greenish grey, laminated to massive and often bioturbated, though the dark colour may obscure the degree of bioturbation present. Bed bases may be sharp and planar with underlying sandstones, or the contact may be gradational with underlying sandstones.

Usually the sandstone and the mudstone form bedded couplets. Where the sandstones grade upward into overlying mudstones, they appear to have been deposited by the same flow event.

Diamictites within this interval are typically black in colour, with sharp bases. The diamictite is unstratified and matrix-supported. Clasts range from granule to pebble size, and comprise mafic volcanic, scoriaceous, and pumiceous fragments sometimes with alteration rims. Clasts range from angular to subrounded.

A distinctive black pumiceous lapilli tuff interval at 588.34 to 590.72 mbsf is made up of several decimetre-thick beds. Individual beds are normally graded, typically with a massive bed toward the base, grading upward through individual beds to planar laminated intervals. Pebble-sized clasts are dominated by volcanic lithic fragments. Two other pumiceous lapilli tuffs occur between 600.21 and 602.95 mbsf, and between 620.69 and 621.07 mbsf. They comprise black, moderately well to poorly sorted, unstratified clast-supported coarse ash to lapilli. Pyrite cement and pyrite grain overgrowths are common, as is carbonate either as a cement or fracture filling.

Lithostratigraphic Subunit 5.2

Phonolitic Lava; 646.49 to 649.30 mbsf (2.81 m thick)

A ~3 m-thick, purplish black, phonolitic lava occurs at 646.49 to 649.3 mbsf. The upper few centimetres of the flow are altered, with a series of alteration bands that are initially calcite, then successively deeper black, grey, and brown. Similarly, the lower contact is also altered—a probable quenched zone, 2 cm thick. Fractures within the flow are generally parallel to the upper contact in the top 1 m, then flatten and parallel the base of the flow in the lower 1.8 m of the lava. Fractures and vugs are filled with calcite.

Additionally, clasts similar in composition to the lava occur within the volcanic sandy diamictite near 675.70 mbsf. The lower contact between the lava and underlying clay/siltstone has a baked layer 1 cm thick.

Lithostratigraphical Subunit 5.3

Volcanic Sandstone, Volcanic Mudstone and Volcanic Diamictite; 649.30 to 688.92 mbsf (39.62 m thick)

LSU 5.3 is very similar to the overlying LSU 5.1 stratigraphic interval, with the two units differentiated on the basis of the intervening lava flow. Similar descriptions therefore are presented for LSU 5.3.

Volcanic sandstones are black in colour due to pyrite diagenesis, and form beds up to 2 m thick. Normal grading is common. Bed bases are usually sharp and erosional (sometimes loaded); tops are

either sharp and planar or gradational. The sand is fine to coarse grained, poorly to well sorted, and composed entirely of volcanic components. Beds are either massive or planar laminated and range from bioturbated to non-bioturbated. Ripple lamination occurs but is rare. Beds commonly display a vertical change in sedimentary structure from massive at the base, to planar laminated in the middle, to ripple-laminated at the top. Beds contain scoriaceous, pumiceous, mafic volcanic, and perigenic siltstone clasts, which are often found scattered throughout the beds. Carbonate and unknown white (non-calcareous) cements are common.

Volcanic mudstone (silty claystone to clayey siltstone) is intercalated with the volcanic sandstones. They form beds up to 1.5 m thick that are black, weakly laminated to massive, and often bioturbated. Bed bases may be sharp and planar with underlying sandstones, or the contact may be gradational with underlying sandstones. Fe-staining is abundant in certain intervals.

Usually the sandstone and the mudstone form bedded couplets, and in many cases, especially where the sandstones grade upward into overlying mudstones, they appear to record a single flow event.

Diamictites within this interval are typically black, volcanic clast-poor, muddy unstratified diamictites up to 2 m thick. The matrix is dominated by sand-sized blue-grey pumiceous grains, with minor amounts of red scoria. Clasts are predominantly granule-sized highly weathered volcanic grains. Several diamictite beds between 659.87 and 663.97 mbsf grade upward from a sandy diamictite to a volcanic medium-grained sandstone to siltstone. A distinctive lithology, likely made up of several beds, occurs at 675.39 to 683.13 mbsf and comprises very angular aphyric mafic, scoriaceous, pumiceous, and intraformational mudstone clasts. Some of the angular clasts exhibit curvilinear margins that terminate in sharp points. A zone of clasts with a 'broken puzzle fit' texture suggests short transport after breakage. Armoured mudclasts also occur in this interval—relatively soft intraformational mudstone clasts that were rolled and 'armoured' by other smaller clasts.

Lithostratigraphic Subunit 5.4

Volcanic Mudstone, Minor Volcanic Sandstone, and Sparse Volcanic Diamictite: 688.92 to 759.32 mbsf (70.4 m thick)

An abrupt change into LSU 5.4 is marked by the abundance of fine-grained deposits, with less common, usually discrete sandstones. The interval is still dominated by volcanic sediments; only toward its base does basement-derived sediment start to become important.

The dominant lithology is dark greenish grey to black, weakly stratified volcanic clayey siltstone and silty claystone, with the two lithologies interlaminated or interbedded at millimetre to centimetre scales. The weak stratification appears to be related to colour and

grain size changes. Bioturbation varies from present to absent within beds. Very fine to fine-grained sandstone is also present. Ripple cross lamination is present in some of the coarse siltstones. Top and basal contacts are either sharp or diffuse and some contacts display flame structures. This lithology can form intervals up to 8.8 m thick without obvious breaks (such as between 714.33 and 723.19 mbsf). Below 723.2 mbsf, isolated red scoria or pumiceous clasts appear within the mudstone, and at 724.92 to 725.18 mbsf, the mudstone contains a small (~10%) biogenic silica content.

Sandstones are subordinate in this LSU and comprise volcanic (pumiceous) fine- to medium-grained sandstone, typically grading upward to volcanic silty claystone. Structures within the sandstones include weak horizontal stratification as well as ripple and climbing ripple lamination. Bases of beds are sharp and either planar or display minor (up to 2 cm scale) relief often associated with loading. The presence of bioturbation is again variable, and may be absent in some beds.

At 750.54 to 751.01 mbsf, a volcanic-rich, clast-rich muddy diamictite is the first indication of basement-derived clasts which have been absent since LSU 4.3. Clasts are granule to pebble sized, and include granitoids, metasediments, minor abundances of volcanics, and mudstone intraclasts. The clasts are subrounded to subangular, in a matrix that contains volcanic glass (25%), 40% minerals, and 30% clay aggregates. A well-developed stratification is caused by colour variations due to mud laminae, horizontal alignment of clast long axes, and grain-size variations.

Lithostratigraphic Subunit 6.1

Volcanic-bearing Mudstone with Dispersed Clasts, Volcanic-bearing Diamictite, Volcanic-bearing Sandstone and Conglomerate/Sandy breccia: 759.32 to 897.95 mbsf (138.63 m thick)

Lithostratigraphic unit 6 is marked by a range of different lithologies, the presence of Transantarctic Mountain (TAM) clastic material, and apparent lack of bioturbation.

A significant change occurs at 759.32 mbsf, to a volcanic-bearing diamictite, which marks a return to more abundant coarser-grained sediments and the return of clastic material derived from the Transantarctic Mountains (TAM) in the diamictites, the conglomerates, and the intercalated mudstones. Below 793.14 mbsf, volcanic-derived sediment falls below a 10% threshold (by and large), although volcanic clasts are still present, and intervals below 850 mbsf have no volcanic material. It is also noteworthy that bioturbation is absent from both the sandstone and mudstone beds in this LSU. An exception is an interval at 851.6 to 853.11 mbsf, where bioturbation is reported. With the very dark colour, it was difficult or impossible to identify bioturbation conclusively. We chose the conservative approach with respect to identifying bioturbation. There is a core break at the

base of this lithostratigraphic interval, so the exact basal contact is not known.

Very dark grey to black mudstones with dispersed clasts are the most frequently occurring lithology, which forms intervals up to 3.5 m thick. The mudstones are volcanic-bearing and usually contain dispersed clasts. In large part the mudstones are unstratified, but some contain centimetre-thick lenses or interbeds of fine- to medium-grained sandstone, or millimetre-thick laminae of siltstone. Smear slides indicate that the glass in the mudstones is brown, rather than the clear or green glass found in the overlying LSU 5.1–5.4. The dispersed clasts are predominantly subrounded to subangular granules and small pebbles, and include granitoids, volcanic lithics, and metasediments. One mudstone between 809.07 and 810.09 mbsf is biosiliceous.

The diamictites form beds up to 4.3 m thick and comprise very dark grey, unstratified to weakly stratified, volcanic-bearing to volcanic-rich, clast-rich muddy diamictite. Clasts are angular to rounded, granule to cobble size (up to 8 cm diameter), and include a variety of lithologies from granitoid, metamorphic, and volcanic (including dolerite) sources plus diamictite intraclasts. Most clasts are <1 cm in diameter.

Light grey to dark grey, centimetre- to decimetre-thick, fine to very coarse-grained sandstones are common through the LSU, and typically grade upward. Sharp bases, sometimes with load features, are common.

Mudstone intraclast conglomerates occur at 819.43 to 820.62 mbsf, 820.73 to 821.73 mbsf, and 822.04 to 822.32 mbsf, and consist of very dark grey, clast-supported conglomerates typically associated with carbonate cement. Clasts are up to 1 cm in diameter and exhibit elongate shapes that appear to have been compressed.

Centimetre-thick beds of muddy breccia occur between 826.77 and 828.42 mbsf. The breccias are light grey to grey in colour and fine upward from a medium-grained sandstone at the base to muddy sandy breccia at the top. Clasts comprise angular volcanic and mudstone granules, and beds grade upward into mudstone and sandy mudstone at the top of each unit.

Lithostratigraphic Subunit 6.2

Muddy Diamictite: 897.95 to 920.51 mbsf (22.56 m thick)

LSU 6.2 is a dark-coloured muddy diamictite that contains a range of basement-derived TAM clasts and is not bioturbated. As for the unit above, the dark colour of the rock made it difficult or impossible to confidently identify bioturbation. There is a core break at the top of this lithostratigraphic unit, so the position and nature of the upper contact is not known.

The dominant lithology is a black to very dark grey, muddy diamictite that ranges from massive to faintly planar laminated. The dark colour is thought to represent diagenetic pyrite. Clasts range

in composition from felsic volcanic to intermediate-grade metamorphic, granitoid, sedimentary, and metasedimentary and are rounded to angular. Most clasts are granule to small pebble size. Elongate clasts are often aligned horizontally, but most clasts are more equant. Millimetre-scale calcite-filled fractures are common throughout.

A subordinate lithology consists of centimetre-thick, very dark grey to black fine sandstone, interlaminated with silty claystone containing dispersed clasts.

Lithostratigraphic Subunit 6.3

Mudstone-dominated, with Muddy Diamictite & Sandstone: 920.51 to 1063.42 mbsf (142.91 m thick)

LSU 6.3 is characterised by mudstone-dominated lithologies, with less abundant intercalated muddy diamictites and sandstones. Also of note, LSU 6.3 contains a relatively low abundance of ice-rafted TAM or volcanic clasts, and their abundance decreases downhole. In addition, the LSU lacks clearly identifiable bioturbation in the core.

The dominant lithologies are mudstones with dispersed or common clasts, sandy to clayey siltstones and silty claystones.

Mudstones with dispersed or common clasts form intervals up to 14 m thick (such as between 977.94 and 992.32 mbsf). They are very dark grey, massive to weakly horizontally stratified, with common branching calcite-filled fractures. Clasts are granules to small pebbles and include a range of lithologies such as granitoids, felsic and mafic volcanics, metasediments, and diamictite intraclasts.

The sandy to clayey siltstones comprise dark grey to very dark grey, often interlaminated or intermixed very fine sandstone and clayey siltstone. Where interlaminated, millimetre-thick sandstone interbeds or cyclopsams may be present (such as at 1030.5 to 1031.68 mbsf). Silty claystones are very dark grey to black and unstratified, and often include branching calcite-filled fractures. They form beds up to 5 m thick. Pinstripe cyclopel laminations are common, particularly in the interval 1033 to 1046.3 mbsf. Lonestones, if present, tend to be small (up to pebble size) and decrease in abundance downcore. Folded and faulted intervals are common.

Muddy diamictites tend to be clast-poor, with clast abundances generally close to 5%, very dark grey to black and unstratified, although individual elongate clasts may display a crude horizontal alignment. Clasts are rounded to angular, range from granules to large pebbles or in rare cases to cobble size, and include a range of lithologies; metasediments, granitoids, felsic and mafic volcanics, as well as mudstone and diamictite intraclasts. Muddy diamictites form intervals up to 12 m thick, and are usually sharp-based, though two muddy diamictites (at 977.94 and 1053.3 mbsf) have bases that are slightly gradational over a few millimetres.

Sandstone beds include dark grey to grey, moderately well sorted, very fine- to fine-grained

ripple-laminated sandstones (such as at 1 031.68 to 1 032.54 mbsf), as well as very dark grey to black, very fine- to medium-grained, moderately sorted, massive to planar and ripple-laminated sandstones, up to 0.2 m thick.

Conglomerates are rare in LSU 6.3 with examples at 949.37 to 949.55 mbsf, a coarse-grained sandstone to muddy sandy conglomerate, and at 978.55 to 979.06 mbsf, a sandy muddy conglomerate.

Lithostratigraphic Subunit 6.4

Muddy Diamictite and Mudstone with Sandstone: 1063.42 – 1220.15 mbsf (156.73 m thick)

LSU 6.4 is dominated by muddy diamictite with subordinate mudstone and sandstone lithologies. Like other LSUs in Lithostratigraphic unit 6, LSU 6.4 is dominated by clasts derived from the TAM, and is apparently not bioturbated, though the dark colour caused by pyrite diagenesis made it difficult to recognize bioturbation.

Muddy diamictite forms intervals up to 14 m thick, and is the dominant lithology that makes up the LSU. The diamictites are dark grey to reddish black, with granule to small pebble clasts that are rounded to angular, and include granitoids, volcanic and sedimentary lithics, mudstone intraclasts, and metasediments. Volcanic clasts are less abundant in LSU 6.4 than in diamictites higher in the core. TAM lithologies are common throughout and reach cobble-size (17 cm maximum diameter). Most of the diamictites are massive, though weak stratification may be present, marked by variations in clast size and abundance, and by horizontal alignment of clast long axes. Diamictites may be interbedded with 1–15 cm-thick dark grey mudstone interbeds or lenses. Rare foraminifera and thoracospheres were routinely observed in smear slides throughout the interval.

A mudstone with common or dispersed clasts, typically occurs beneath the diamictite. The mudstones are very dark grey to black, with granule to small pebble clasts which are metasediments, granitoids, volcanics and mudstone intraclasts. Clasts are angular to rounded, and dispersed pyrite is common throughout. Lamination is common in certain intervals. These mudstones typically occur above very dark grey to black, weakly stratified, strongly pyritised silty claystone. Between 1 061 to 1 062.42 mbsf, the silty claystones are interbedded with very dark grey sandy mudstones.

Stratified fine-grained sandstone, forming beds up to 7 cm thick, occurs between 1062.42 and 1063.42 mbsf. These beds are composed of well-sorted fine-grained sandstone with millimetre-scale parallel laminations, and occur interbedded with centimetre-thick, poorly sorted coarse-grained sandstone.

A black conglomerate occurs at 1173 to 1173.91 mbsf. It fines upward, with the largest clasts at the base up to 2 cm in diameter, and including granitoids, volcanic lithics, and mudstone intraclasts.

Lithostratigraphic Subunit 7.1

Volcanic Sandstone and Volcanic Mudstone: 1220.15–1275.24 mbsf (55.09 m thick)

A change at 1220.15 mbsf marks a shift to black interstratified volcanic sandstones and mudstones. These sediments are recognised as a new lithostratigraphical unit. The upper contact of LSU 7.1 is thought to mark the 'bilious green seismic reflector', the pre-drill target for AND-1B.

Sandstone beds are up to 1 m thick and comprise dark grey to black, fine- to coarse-grained, graded or non-graded volcanic sandstone. Many beds display a massive basal interval, grading upward into planar laminated sandstone. Bases of beds are usually sharp and may display load casts, and tops are sharp and planar, or irregular due to soft sediment deformation, or gradational into overlying intervals. Centimetre-thick sandstone beds often display ripple lamination. One interval between 1221.6 and 1222.06 mbsf comprises several beds of well stratified sandstone, with laminae oriented up to 15° across the core.

Sandstones are interbedded with black volcanic-bearing silty claystones, and form bedded intervals up to 1.5 m thick. The mudstones are massive or stratified by 1–10 mm thick laminae. Pyrite cementation is moderate to pervasive and often obscures original structures and textures. Often the sandstones and silty claystones are interbedded at a centimetre-scale. Clasts of granule-size volcanic lithics or granitoids are dispersed through the mudstones.

Less frequently occurring lithologies include (i) very dark grey to black, clast-rich muddy diamictite, often intermixed with silty claystone and fine sandstone, and (ii) very dark grey, volcanic sandy granule to pebble conglomerate.

Lithostratigraphic Subunit 8.1

Diamictite: 1 275.24 – 1 284.87 mbsf (9.63 m thick)

The final few metres of the core pass into a clast-rich muddy diamictite, with the clasts dominated by TAM debris. Both massive and crudely stratified diamictite is present, and is intercalated with a few beds of mudstone with dispersed clasts and very dark grey stratified siltstone. In the basal few metres, muddy diamictite grades into sandy diamictite.

FACIES DESCRIPTION

Eleven facies are identified on the basis on lithological, sedimentary, and textural characteristics. Where possible, facies recognition is based on assigned descriptive names, or an association of several lithological characteristics. Terminology refers to lithified forms (suffix '-stone' or '-ite'), although some sediments in the upper parts of the core are unlithified.

FACIES 1–DIATOMITE

Facies 1 consists of massive to weakly stratified diatomite (Fig. 2). Locally, the diatomite is thinly laminated, as defined by colour changes or laminae/beds of sandstone and gravel. Some of the colour-defined laminae contain monospecific assemblages of diatoms (e.g. 194.96 to 195.12 mbsf). Dispersed pebbles, granules and coarse sand are common throughout, and are predominantly mixed volcanic lithologies, although Transantarctic Mountain (TAM) lithologies and diamictite intraclasts also occur. Lonestones are commonly associated with sandy to granule-grade laminae/beds, and may deform the laminae beneath. Zones of pervasive bioturbation

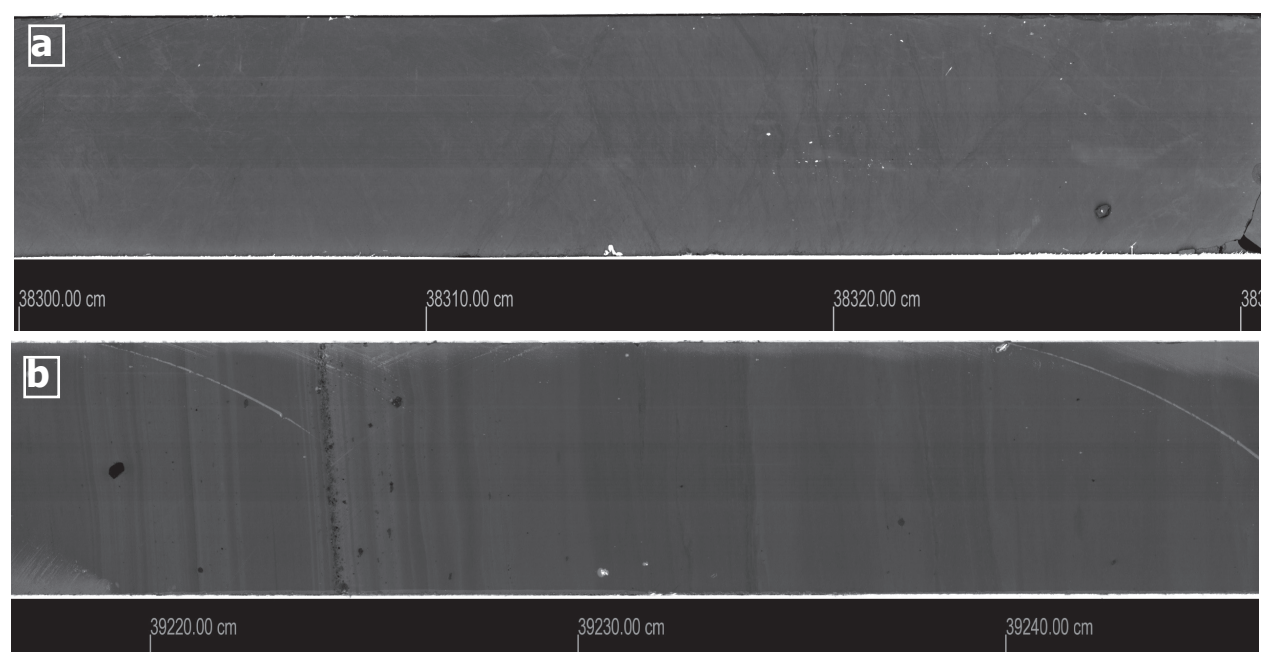


Fig. 2 – (a) Facies 1–Diatomite. Massive diatomite with low terrigenous content at 383.00–383.30 mbsf (Facies 1a). Anastomosing fractures produce a brecciated appearance. Scale shows 10 cm divisions. (b) Facies 1–Diatomite. Diatomite stratified at millimetre- to centimetre-scale, 392.15–392.48 mbsf (Facies 1b). Stratification caused by slight variations in terrigenous content, including coarse sand and granules. Scale shows 10 cm divisions.

often obscure original stratification. The degree of bioturbation is variable and commonly consists of simple horizontal, millimetre-scale ovoid burrows, although several different styles of trace fossils on the millimetre- to centimetre-scale are present. Faulting is common throughout, although it is usually more intense in the upper sections of the diatomite units, particularly when overlain by diamictites (Facies 9 and 10). We have assigned two subfacies, which are identified by the abundance of terrigenous sediment. Facies 1a consists of an almost pure diatomite lacking a significant terrigenous component, *i.e.* diatomite with limestones and occasional sandstone/gravel laminae or beds, while Facies 1b consists of terrigenous-bearing to terrigenous-rich (10%–50% lithic component) diatomite, indicating mixing of the biosiliceous component with fine-grained terrigenous sediment.

Facies 1 represents pelagic sedimentation in a marine environment, although periods of iceberg rafting are recorded throughout. The division into subfacies distinguishes between a sedimentary environment that is dominated almost entirely by pelagic settling from one that is dominated by pelagic settling combined with a significant input from hemipelagic suspension settling or a contribution from icebergs.

FACIES 2- MUDSTONE

This facies is subdivided into silty claystone (Facies 2a) or clayey siltstone (Facies 2b), both predominantly massive in structure (Fig. 3). If present, stratification is identified by a change in either colour or particle size, with locally occurring sandstone laminae or thin beds (millimetre to centimetre scale). Sandstone laminae and beds are

predominantly volcanic in composition, and may be massive or graded. They often display planar or ripple laminae. Bioturbation intensity varies and may be so pervasive that it obscures primary stratification, although bioturbation may also be obscured by a strong pyrite overprint. In addition, bioturbation is absent in many intervals, and tends to increase in sections near contacts with Facies 1. Soft-sediment deformation features are common throughout. Lonestones are rare but appear to be more common when bioturbation is present. Below 759.32 mbsf, bioturbation is absent to extremely rare, whereas limestones continue through to the base of the core. A biosiliceous component is common above 586.59 mbsf, whereas it is rare to absent below this depth. Single fragments of macrofossils are extremely rare.

Facies 2 represents environments that may be either distal or proximal to grounded ice and are dominated by hemipelagic suspension settling. An increase in bioturbation suggests a more distal environment, whereas non-bioturbated mudstone is thought to represent a more proximal grounding-line environment. This is particularly evident in the lower part of the core, where the lack of bioturbation in 5–10 m-thick mudstones associated with Facies 4, 9, and 10 may represent an environment that was more proximal to grounded ice, where sedimentation rates were too high to allow infaunal benthic organisms to live. Also, high sedimentation rates may force fines to flocculate and preclude lamination. Alternatively, the heavy pyritisation in this part of the core may have obscured any bioturbation. The absence of diatoms in these units may be due to a high sedimentation rate or may be the result of diagenetic transformation of diatoms to opal C-T.

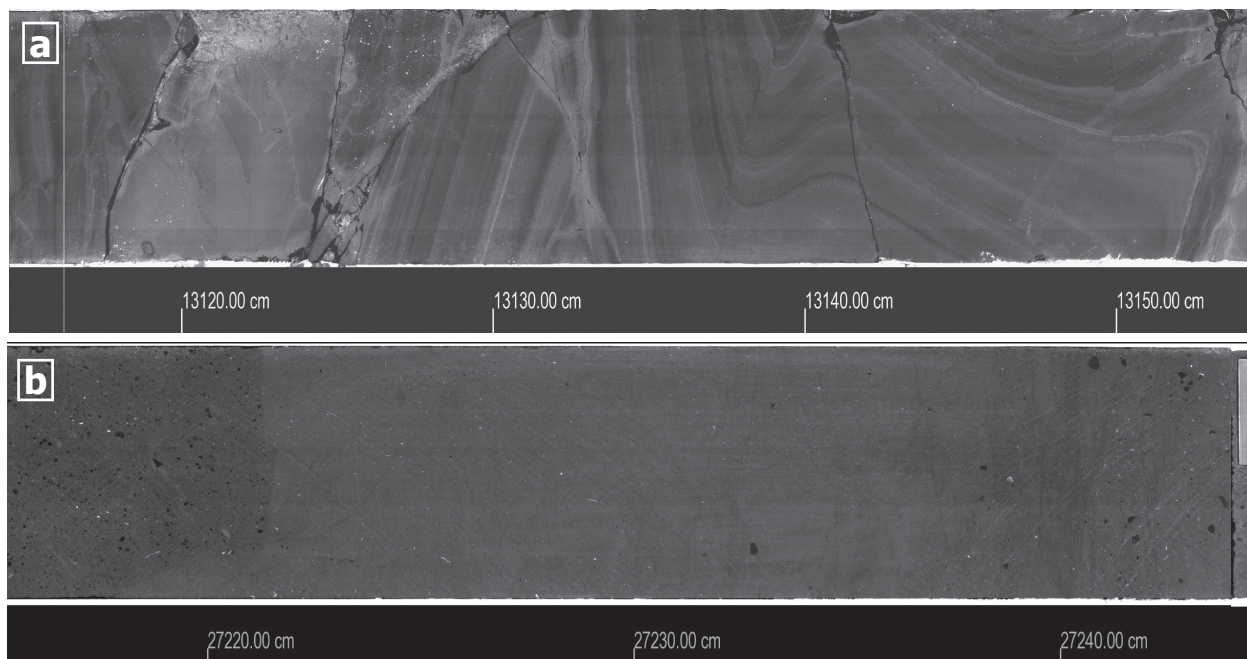


Fig. 3 – (a) Facies 2–Mudstone. Silty claystone (Facies 2a) with centimetre-scale subhorizontal laminations and soft sediment deformation (131.15–131.55 mbsf). (b) Facies 2–Mudstone. Massive clayey siltstone (Facies 2b) at 272.20–272.44 mbsf. The sharp (sheared) contact at 272.20 mbsf is interpreted as a glacial surface of erosion (GSE), overlain by massive clast-rich muddy diamictite.

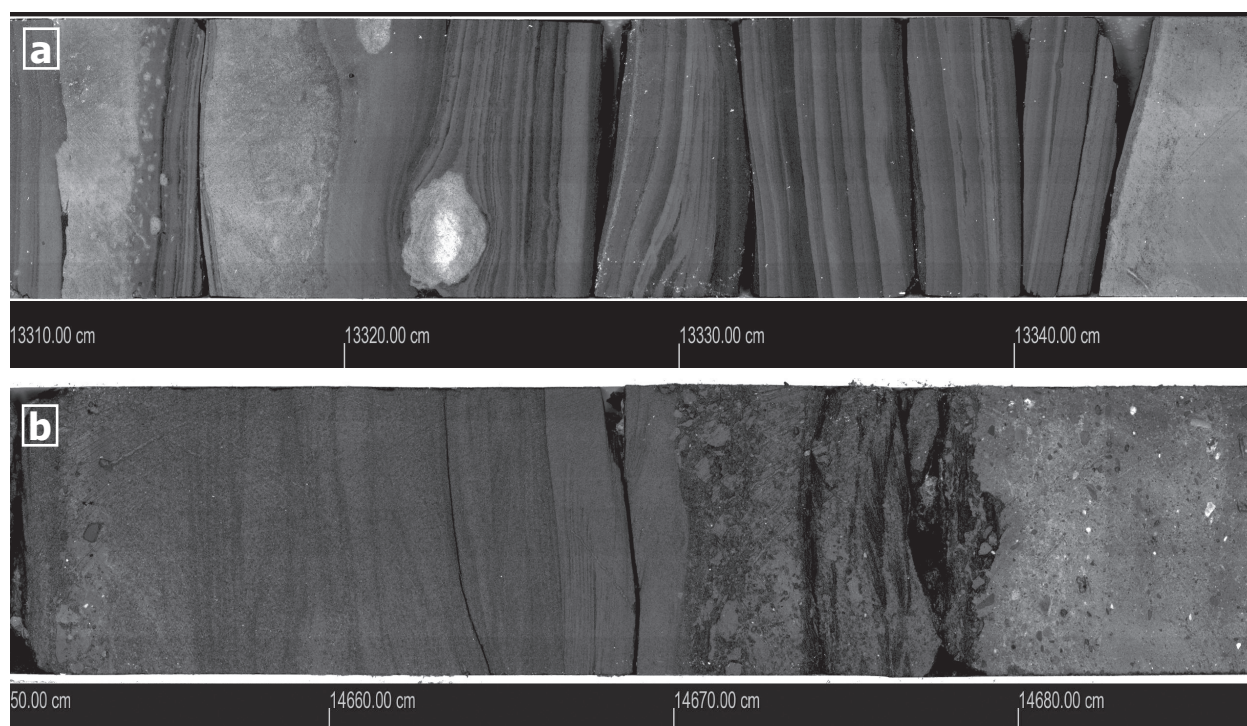


Fig. 4 – (a) Facies 3—Interstratified mudstone and sandstone. Volcanic fine-grained sandstone laminated with siltstone above a sharp contact with clayey siltstone (133.10–133.45 mbsf). A sandstone dropstone depresses the underlying laminae. (b) Facies 3—Interstratified mudstone and sandstone. Facies 3 occurs above the contact with clast-rich muddy diamictite at 146.79 mbsf. Siltstone and sandstone are intercalated by soft sediment deformation at 146.70–146.74 mbsf; the remainder of 146.50–146.79 mbsf comprises parallel and ripple cross-laminated medium sandstone.

When stratified, the siltstone and sandstone laminae may represent a contribution from distal sediment gravity flows, or the winnowing of fines, perhaps related to submarine outwash or bottom currents. In addition, millimetre-scale siltstone and sandstone laminae can also be deposited from turbid plumes by suspension settling, which may be an indicator of the contribution of subglacial meltwater. There is also an ice rafting contribution in the form of lonestones and poorly sorted sand beds. Regional volcanic activity may also contribute to the deposition of the sediment gravity flows.

FACIES 3—INTERSTRATIFIED MUDSTONE AND SANDSTONE

Facies 3 consists of mudstones, similar in texture and composition to Facies 2, but interbedded with graded and massive sandstones on a centimetre to decimetre scale (Fig. 4). The sandstones are very fine to medium-grained, and on occasion, reach coarse sand grade. The sandstone beds commonly grade upwards and are associated with a variety of sedimentary structures, notably planar and ripple lamination - although massive beds also occur. The lower contacts of the sandstones are usually sharp, and upper contacts are gradational. The composition of the sandstone beds is variable, with some intervals dominated by volcanically derived grains, whereas others display a diverse range of minerals, including relatively high proportions of quartz and feldspar. Lonestones of various lithologies are common, and occasionally deform underlying

laminae. Thin diamictite beds are included in some intervals. Bioturbation is often present within finer grained intervals, and notably are more common near contacts with Facies 1. Soft-sediment deformation is also present in some intervals.

The generally fine-grained nature of this facies and the relative lack of macrofossils indicate deposition in a deepwater marine environment. The interbedded nature of this facies is likely to be the combination of hemipelagic sedimentation derived from turbid plumes with distal to proximal sediment gravity flows resulting from grounding-line fan processes or volcanic/tectonic activity. Increasing abundance and coarseness of planar and ripple-laminated sand units with a notable quartzo-feldspathic component indicate proglacial grounding-line fan processes. In addition, ice rafting processes may also result in an increase of sand grains and clasts with diverse lithologies. Traction currents are another likely process for this facies, with either the reworking of the tops of gravity flow deposits or separate (discrete) traction currents.

FACIES 4—MUDSTONE WITH DISPERSED/COMMON CLASTS

Facies 4 consists of silty claystones or mudstones that contain dispersed (<1%) or common (1%–5%) clasts (Fig. 5). Clasts are predominantly granules to small pebbles with diverse lithologies. Facies 4 commonly grades into and out of massive and stratified diamictites, and mudstones with clasts are often only distinguished from the diamictites of

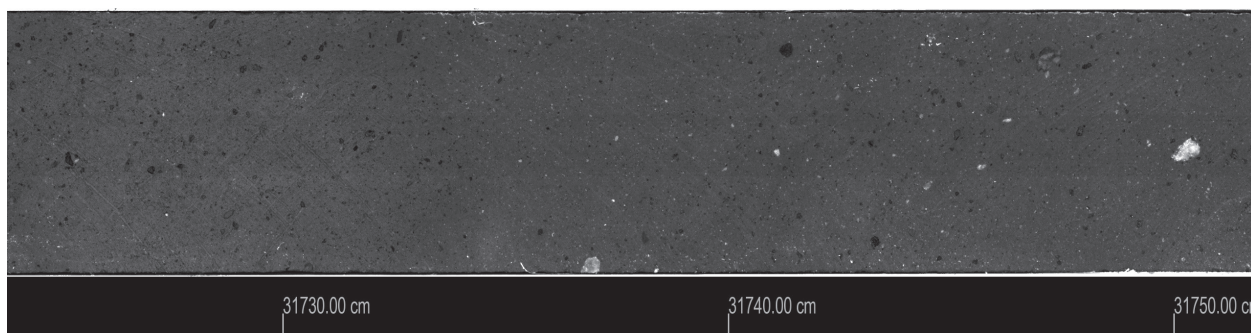


Fig. 5 – Facies 4: Mudstone with dispersed/common clasts. Biosiliceous-bearing sandy mudstone with dispersed clasts at 317.22–317.52 mbsf. Clasts are commonly granule-size mafic volcanics, although other lithologies are represented. Pebbles are rare.

Facies 9 and 10 by a decrease in the sand component of the matrix below 10%. Bioturbation can be locally pervasive, but is often absent. Faulting and fracturing are common, particularly when Facies 4 occurs below diamictite. Stratification, if present, is defined by changes in colour and grain size. We have divided the facies into unstratified (4a) and stratified (4b) subfacies. Diatoms are rare to absent below 558.75 mbsf.

This facies may represent an environment similar to that of Facies 2, with the presence of dispersed/common clasts indicating rainout from floating ice, either beneath an ice shelf or from icebergs. In association with Facies 10, units that lack bioturbation may indicate deposition beneath grounded ice. The presence of bioturbation suggests a marine environment that is relatively distal to proglacial processes. The high mud content is interpreted as representing hemipelagic sedimentation derived from turbid plumes in a pro-grounding-line marine environment, with clasts being contributed from floating ice. High sedimentation rates are suggested by an absence of bioturbation and microfossils.

FACIES 5 – RHYTHMICALLY INTERLAMINATED MUDSTONE WITH SILTSTONE OR SANDSTONE

Facies 5 consists of mudstones, similar in texture to Facies 2, which are rhythmically interlaminated with siltstone or very fine-grained sandstone (Fig. 6). These interlaminated intervals commonly grade out of Facies 3, 9, or 10, and into Facies 2 or 3. Claystones and siltstones form fining-upward couplets that are bundled into 2 to 5 cm-thick packages containing 6–10 couplets on either side of a claystone-dominated

lamina, up to 2 cm thick. Individual couplets have a basal lamina of clayey siltstone 2 to 5-mm thick which grades into a claystone lamina 1–2 mm thick. Thinner couplets appear more discrete and well sorted; thicker couplets appear diffuse, contain more mudstone and are less well sorted. Couplets vary systematically in thickness within each package, producing a strong rhythmicity. Mudstones can be interlaminated with sandstone in the coarser part of each couplet. The best example of Facies 5 occurs from 1038.88 to 1046.16 mbsf. Facies 5 is associated with lonestones that form impact structures in the underlying laminae. Lenses and beds of poorly sorted medium to coarse sand and granules also occur.

This facies was deposited in a quiet water basin by suspension settling from meltwater plumes. These couplets are termed cyclopsams (sandstone/mudstone) for the coarser, more ice-proximal deposits and cyclopels (siltstone/mudstone) for the finer, ice-distal equivalents. The rhythmicity may result from turbid plumes interacting with tidal currents near the top of the water column to modulate the release of suspended sediment that settles to the seafloor. Icebergs contributed dropstones and poorly sorted sandstone beds.

FACIES 6 – SANDSTONE

Facies 6 consists of interbedded siltstones, muddy sandstones, and very fine- to coarse-grained sandstones (Fig. 7). The beds are predominantly volcanic rich and commonly black in colour, and occasionally contain mud rip-up clasts. Normal grading is common, although massive beds are present. Many beds display planar lamination, and cross-stratification

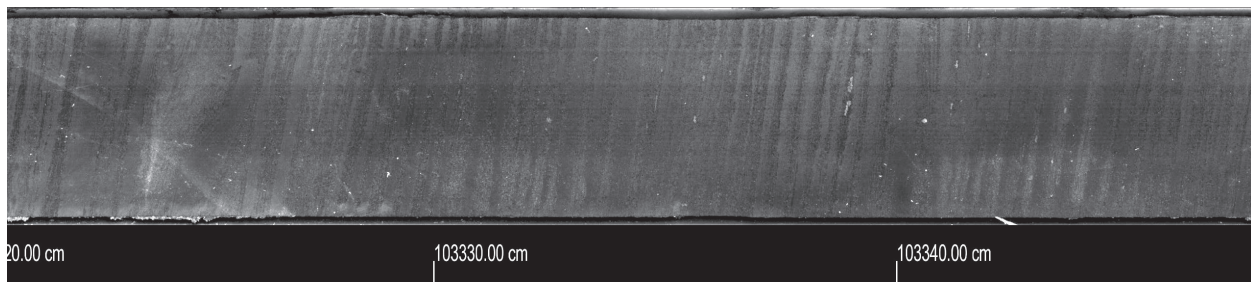


Fig. 6 – Facies 5: Rhythmically interlaminated mudstone with siltstone or sandstone. Regularly spaced couplets from 2 to 5 mm thick of very fine sandstone grading into siltstone (1 033.22–1033.47 mbsf). Most sandstone laminae are sharp-based, with gradational upper contacts into siltstone. These couplets are termed cyclopsams.

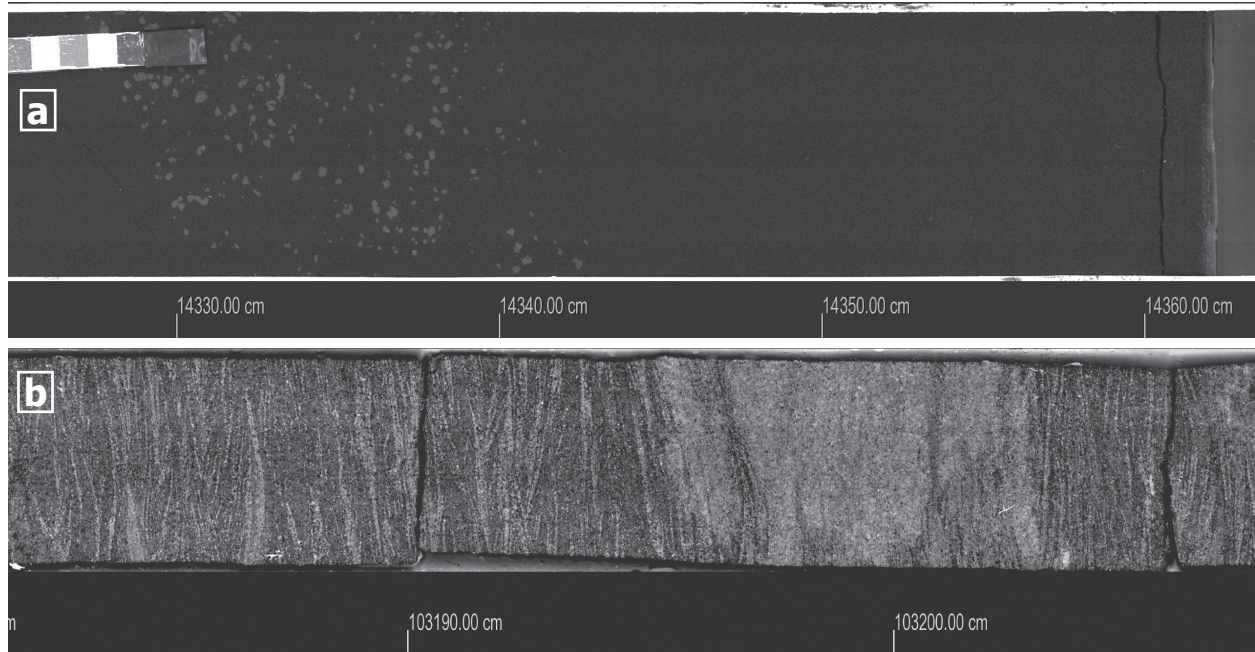


Fig. 7 – (a) Facies 6: Sandstone. Siltstone grading up to medium sandstone (143.25–143.62 mbsf). Sand is composed of 100% volcanic glass. Above 143.41 mbsf, sand contains millimetre-scale small spherical carbonate-cemented nodules (SSCCN). (b) Facies 6: Sandstone. Very fine to fine sandstone with ripple cross-lamination in sets 0.5–1.0 cm thick (1031.80–1031.95 mbsf).

is relatively rare. Reverse-graded sandstone beds are also present but are less frequently encountered. Bed bases are usually sharp and irregular, whereas tops are either gradational or sharp and planar. Soft-sediment deformation structures are common in some intervals. The sandstones are often interbedded with sandy mudstones or siltstones, which are either massive or laminated.

This facies is interpreted as turbidites. Incomplete Bouma sequences with Ta (massive) and Tb (planar laminated) grading upward into Te (massive mudstone) beds are common; while complete

Bouma sequences from Ta to Te divisions do occur, they are generally rarer. The incomplete sequences are interpreted as fines-depleted turbidites in which the coarser-grained Bouma Ta and Tb divisions predominate, and the lower density Bouma Tc to Te divisions have been deposited further downslope. The sandstones usually contain reworked volcanic sediment, and probably originated on slopes made up of volcanic material. These flows may have been triggered by co-seismic activity related to volcanism. Reverse graded beds may represent subaqueous flows of increasing strength or sediment supply, or

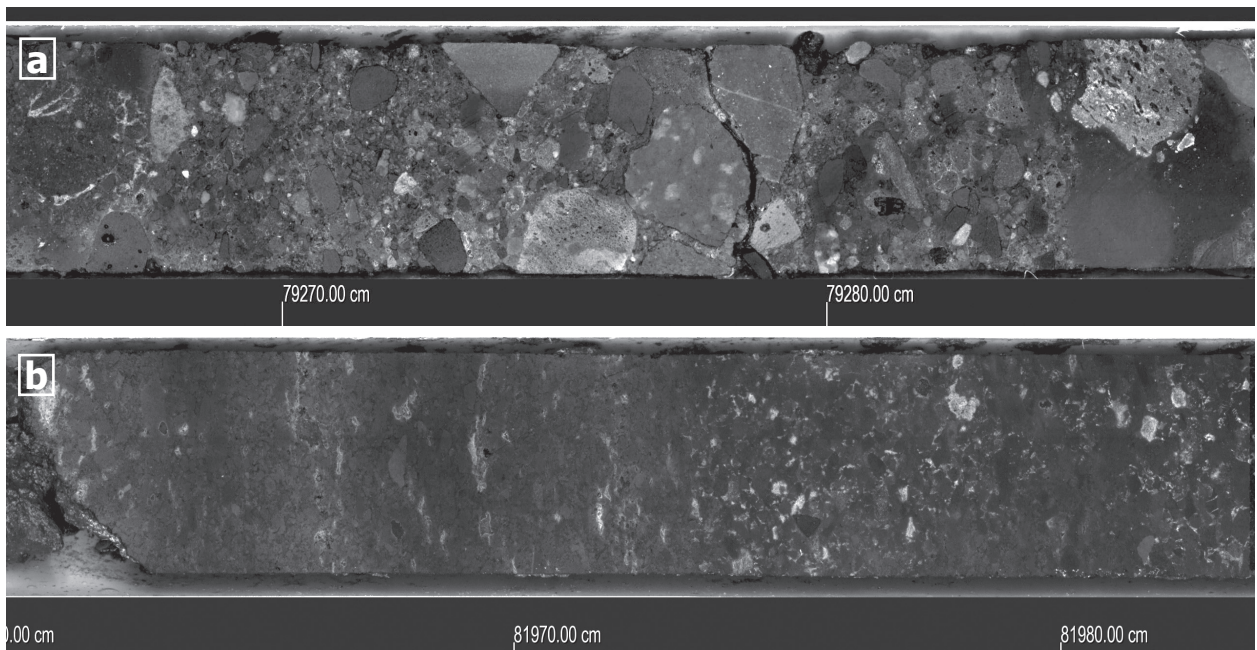


Fig. 8 – (a) Facies 7: Conglomerate. Volcanic-bearing muddy sandy conglomerate, weakly stratified by variations in grain size. Clast composition is estimated at 90% volcanic, 10% granitoid, and a trace of metasedimentary (792.63–792.89 mbsf). (b) Facies 7: Conglomerate. Mudstone intraclast conglomerate is stratified at centimetre-scale by grain size and intraclast shape variations between elongate and equant (819.61–819.84 mbsf).

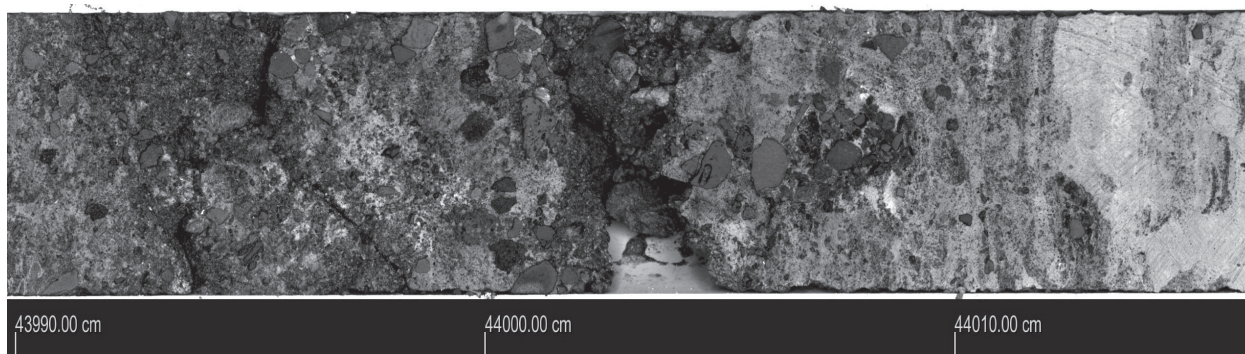


Fig. 9 – Facies 8: Breccia. Diatomite-rich volcanic muddy sandy breccia. Clasts include a variety of lithologies (439.90–440.16 mbsf).

may represent flows where density settling of particle sizes has occurred.

FACIES 7—CONGLOMERATE

Facies 7 is a matrix- to clast-supported sandy muddy conglomerate (Fig. 8). Clasts are generally rounded to subrounded and of diverse lithologies, including volcanics, granitoids, metamorphics, diamictite, and mudstone intraclasts. The conglomerates are often weakly stratified, and are generally <2 m thick. Some conglomerates (e.g. between 820.66 and 821.74 mbsf) are composed of >90% mudstone intraclasts that are elongate and horizontally aligned. Lower contacts are sharp and irregular, and generally have relief of ~1 cm, except when associated with Facies 4, 9, or 10, when contacts are often gradational. Facies 7 is uncommon within the core.

This facies is likely to represent submarine sediment redeposition, possibly during turbulent subglacial conduit discharges.

FACIES 8—BRECCIA

Facies 8 is a poorly sorted breccia that consists of sand, granule and gravel clasts in a muddy or sandy matrix (Fig. 9). The clasts are dominated by angular to subrounded granules and pebbles. Clasts are usually dominated by volcanic lithologies and/or mud intraclasts, although other lithologies such as metasediments and diamictite intraclasts also occur. In some units, large clasts appear to be concentrated at the top of the unit. Soft-sediment deformation, sediment flow and clast rotation features

are common. The lower contacts of the breccias are usually sharp and irregular erosional surfaces and vary from horizontal to inclined (<30°). This facies is interpreted to have formed by sediment redeposition by mass-flow processes, perhaps from a volcanic source.

FACIES 9—STRATIFIED DIAMICTITE

Facies 9 consists of clast-rich to clast-poor diamictite. Stratification ranges from weak to well-defined, and is identified by changes in colour, clast concentration, or particle size (Fig. 10). Horizontal alignment of clasts is not used as a criterion for stratification, although preferred a-axis orientation commonly occurs. The texture of the matrix may be muddy or sandy, and the biogenic silica content is also variable, ranging from absent to biosiliceous rich (i.e. comprising up to 50% of the matrix). Clasts are angular to rounded, poorly sorted, and comprise a wide range of lithologies, including volcanic, metasedimentary, sedimentary, granite, dolerite, marble, and mudstone intraclasts. Outsized clasts are present in some intervals. Facies 9 is often interbedded with, or grades out of, Facies 10. Macrofossil fragments do occur but are extremely rare. Bioturbation is present in some intervals, but is rare.

The genetic origin of the stratified diamictites is diverse. Thinner beds associated with marine facies (e.g. Facies 1) are likely to have been formed by ice rafting or debris flow deposition. For units that are associated with ice contact or proglacial facies (e.g. Facies 3, 4, and 10), depositional processes may include rainout of basal glacial debris and associated

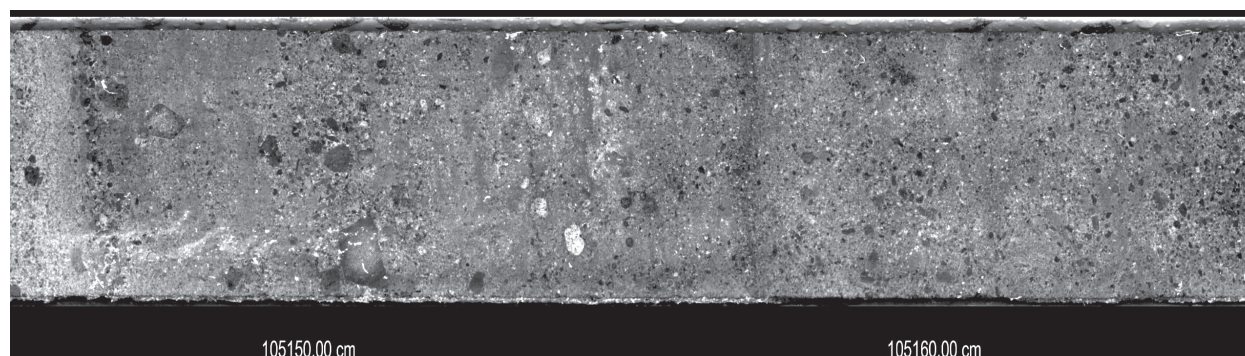


Fig. 10 – Facies 9: Stratified diamictite. Clast-rich sandy diamictite, stratified by variations in grain size and clast concentration. Clast-free interbeds coarsen upward, from stratified claystone below 1051.60 mbsf to very fine sandstone above 1051.54 mbsf.

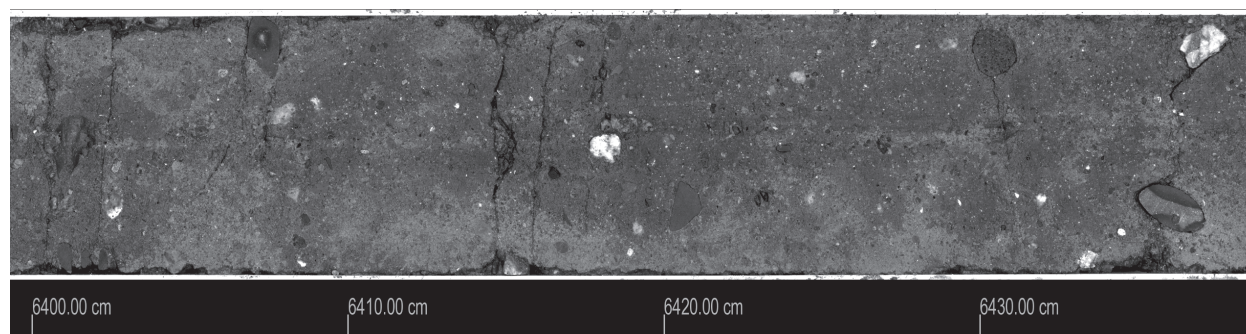


Fig. 11 – Facies 10: Massive diamictite. Clast-rich muddy diamictite from 64.09 to 64.38 mbsf. Clast composition is variable, including mafic volcanics and granitoids.

reworking by marine outwash, or by debris flows from the grounding line. Alternatively they may be deposited beneath grounded ice.

FACIES 10–MASSIVE DIAMICTITE

In general, the textural and compositional characteristics of Facies 10 are identical to those of the stratified diamictites of Facies 9 (Fig. 11). Although there is no stratification, alignment of clast a-axes does occur in some intervals. Sharp lower contacts are often associated with load features, and fracturing is also common. The mud, sand, and clast contents are variable, and the diamictite may be interbedded with, or grade into and out of, Facies 4 or 9. Clast roundness is also variable, ranging from angular to rounded.

This facies is likely to represent subglacial deposition, although rainout from floating ice and mass-flow processes are other possibilities. When this facies occurs with a sharp basal contact with the underlying facies and an underlying zone of physical mixing, it is taken to represent deposition beneath grounded ice and is interpreted as a till.

FACIES 11 – VOLCANIC ROCKS AND SEDIMENTS

This facies consists of primary and near-primary volcanic deposits (Fig. 12). It includes volcanic diamictites, lapilli tuffs, and one phonolitic lava flow (646.49 to 649.3 mbsf). With the exception of the lava flow, all deposits have undergone some redeposition. Volcanic units that show significant reworking are included in the sedimentological facies described above, and are noted with the suffix 'V'.

Tuffs and lapilli tuffs are generally well sorted, and range from fine (mud-size) ash to lapilli. Lapilli are clast-supported, and sorting/bedding may be obscured by alteration, although normal grading is present in some units. The clast-rich to clast-poor volcanic sandy diamictites are commonly black in colour and may be weakly stratified, as defined by clast abundance. However, the volcanic diamictites commonly are unstratified. Clasts are predominantly angular and granule grade. They are limited to a range of volcanic lithologies, including black vesicular, pumiceous, and red scoria granules and pebbles. The matrix is composed of abundant volcanic glass, and some clasts are highly altered. Basal contacts are sharp and irregular, with some showing evidence of loading and injection of underlying units into the diamictite. The diamictite beds are generally less than 2 m thick, and are interpreted as representing high-density mass-flow deposition associated with regional volcanic activity. For details on the lava flow, refer to the 'Lithostratigraphy' section (LSU 5.2).

SEQUENCE STRATIGRAPHIC INTERPRETATION

In the AND-1B core, we recognise more than 50 unconformity-bound glacial-marine sequences. Each sedimentary cycle contains a repetitive vertical association of facies, which are interpreted to represent successive glacial advances and retreats across the continental shelf of the Ross Sea region. We assume that the facies architecture responds to base level changes or to the proximity of ice through

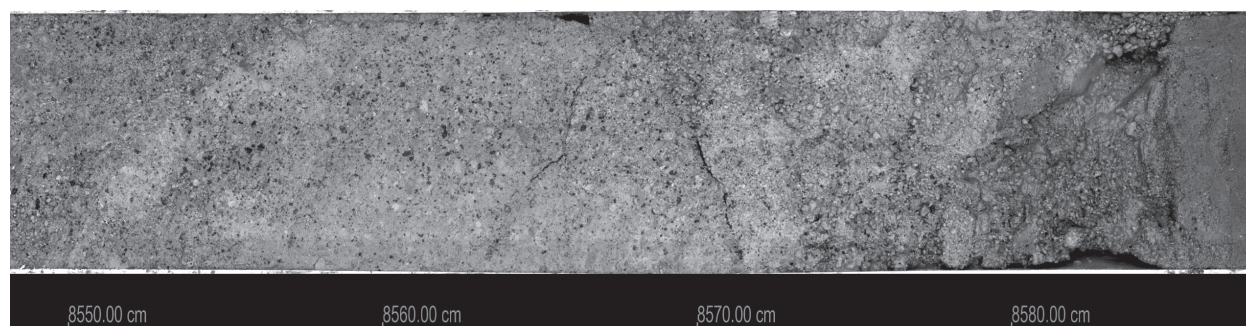


Fig. 12 – Facies 11: Volcanic rocks and sediments. Massive volcanic tuff with abundant dark subrounded clasts (85.48–85.87 mbsf). Volcanic tuff fines upward, as do the included volcanic mudstone rip-ups. Tuff has sharp contacts and is composed of highly angular vesicular glass with rare euhedral mineral grains.

time. Cycles are defined based on vertical changes in facies. The base of each cycle is considered a Glacial Surface of Erosion or GSE (after Fielding et al. 2000), representing the advance of grounded ice across the core site during periods of glacial advance. These surfaces record a period of glacial advance that resulted in erosion of underlying strata, and hence potentially represent hiatuses in the succession. GSEs are identified on the basis of sharp facies dislocations (although some cases amalgamate diamictites), separate diamictite from underlying facies, and can vary widely in character. The underlying deposits are often sheared and display soft-sediment deformation and physical mixing of lithologies. Where an advance of grounded ice is represented by a diamictite that overlies another diamictite, the GSE is difficult to identify due to the amalgamation of the two. In such cases, the GSE is defined on the basis of the facies sequence below, which may include deformed and physically mixed intervals and/or the overlying diamictite that may contain soft-sediment mudstone and diamictite intraclasts. However, in most cases where diamictites are amalgamated, variability in the degree of stratification allows fluctuations in the grounding line to be recognised.

GSEs or cycle motifs have not been recognised in the volcanic successions in the middle part of the core, from 600 m to 760 mbsf, and again from 1220 to 1275 mbsf. We recognise three distinct stratigraphic cycle motifs (labelled 1 to 3 below) from the MIS core (Fig. 13). These cycles have some similarities to the patterns described in the Cape Roberts cores (CPR-2/2A and CPR-3; Fielding et al. 2000, 2001); however, major differences are that there are no shoreline facies or facies that contain diagnostic water-depth indicators. Thus the changes in these cycles are more similar to those of Powell and Cooper (2002), where glacial sequence stratigraphic models are presented without the influence of sea-level change on seafloor deposits.

Diamictite-dominated motif

This cycle motif is dominated by diamictite with little or no finer-grained facies. It represents the only motif present in the upper 82.7 m of the core and in the lower part of the core, at 1083–1168 mbsf and 1275–1285 mbsf. Cycles comprise a sharp, presumed, irregular base above deformed or undeformed diamictite (Facies 9 or 10) or above interlaminated sandstone and mudstone, or thin conglomerate units (Facies 3, 6, or 7, such as at 47.9 mbsf). Massive diamictite (Facies 10) is the dominant lithology comprising the cycle, with subordinate interstratified sandstone and mudstone (Facies 3), sandstone (Facies 6), and mudstone (Facies 2). The finer-grained portions of the cycle motif are inferred to have been erosionally truncated by the advancing ice of the next youngest cycle. In this manner, we infer that a considerable period of 'missing' time may be represented at the top of each of these top-truncated cycles.

Diamictite to diatomite-dominated motif

Motif 2 occurs below 82.7 mbsf to a depth of 586.59 mbsf, and is characterised by a succession that records an ordered ice retreat and the subsequent ice advance. The motif begins with a sharp and erosional GSE overlain by centimetre- to decimetre-thick subglacial till, typically comprising a massive diamictite (Facies 10), and representing an advance of grounded ice. Overlying the diamictites are a series of ice retreat facies, most commonly represented by an upward transition to stratified diamictite (Facies 9) or mudstone with dispersed clasts (Facies 5). These facies represent glacial-marine grounding-line depocentres, ice-shelf, and iceberg zones, and in turn are overlain by sandstone (Facies 6), interstratified sandstone and mudstone (Facies 3), mudstone (Facies 2, with or without cyclopels), and finally, diatomite (Facies 1). This gradation represents the transition from a glacially proximal environment to one that is more distal. Diatomite represents the most open-water and ice-distal depositional conditions of the motif. In some of the cycles, the diatomite interval can be over 80 m thick (such as between 376 and 460 mbsf). The upper portion of Motif 2 is characterised by a similarly ordered stratigraphy that records ice advance. The stacking above the diatomite typically comprises mudstone (Facies 2), overlain by sandstone and mudstone (Facies 3), rhythmically stratified sandstone and mudstone (Facies 5), or conglomerate (Facies 7). We interpret these facies as iceberg zone or ice-shelf deposits. The final phase of the advance succession is represented by stratified diamictite (Facies 9) that is commonly deformed or intermixed with underlying lithologies, immediately below the next GSE. Soft-sediment folding, fractures, and rotated blocks are common, and are attributed to sub-ice deformation and/or ice pushing related to ensuing ice advance. Preservation of this ice-advance succession is significant, especially compared with Motif 1.

Diamictite to mudstone-dominated motif

Motif 3 is common below 590 mbsf and, like Motif 2, records an ice retreat-advance history. It differs from Motif 2 by the total absence of diatomite, with the upper portion of the cycles instead being dominated by terrigenous mudstone. Also, the upper ice-advance portion of the motif tends to be either absent (such as in the cycle at 1048.2 to 1053.3 mbsf), or truncated or thinned (as in the cycle from 821.7 to 855 mbsf). In addition, deformation of units under the GSE is less obvious than in Motif 2.

We are unsure whether this diatomite-terrigenous difference is related to depositional processes, or whether it relates to diagenesis, *i.e.* diatomite was once present but has been transformed to an opal C-T mudstone. However, at the present stage of study, we see sufficient differences to justify differentiating these two motifs.

In all cases, massive diamictite (Facies 10) overlies the GSE. It is always in turn overlain by

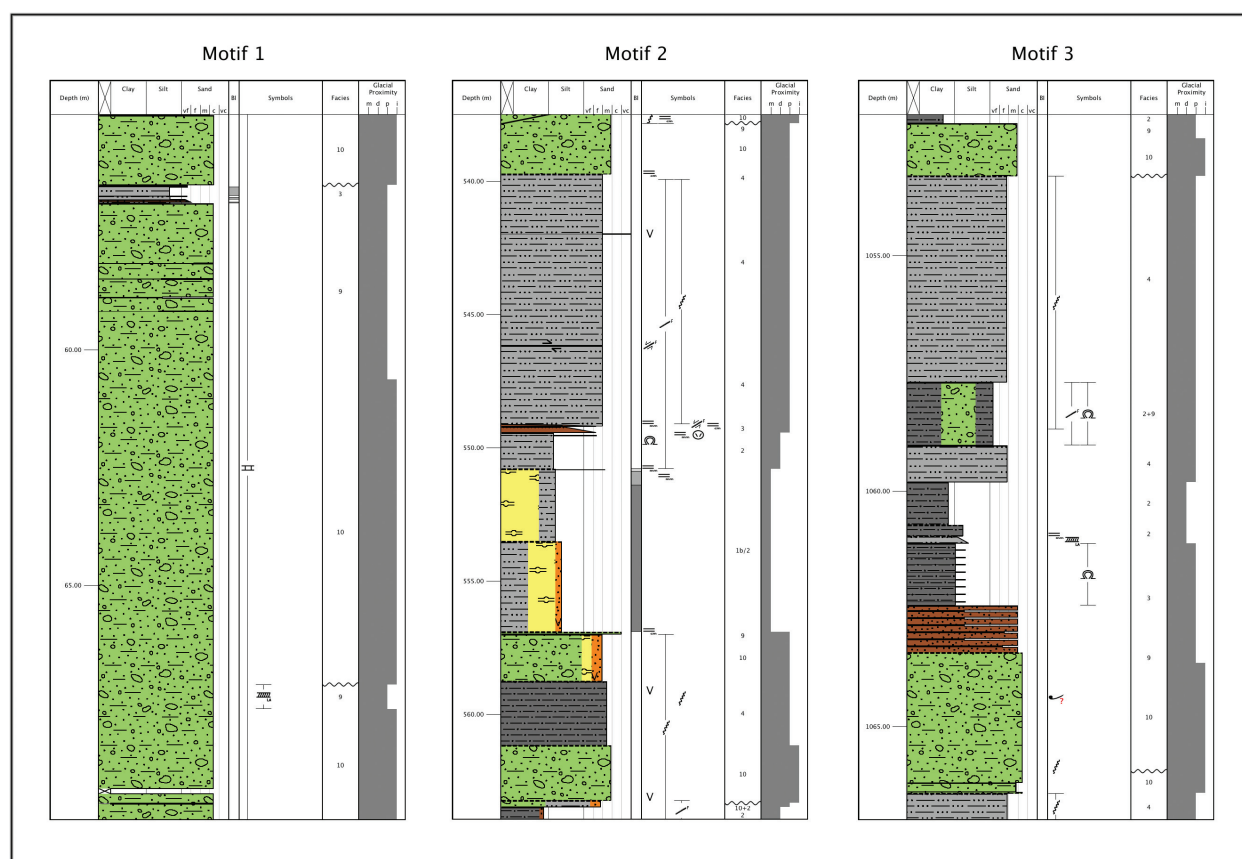


Fig. 13 – Representative examples of the three sequence motifs recognised in the core. Columns to the right of the graphic log show the main sedimentary features by way of symbols (referred to in main logs), facies (see separate facies description), and a glacial proximity graph from ice proximal to distal. The example of Motif 1 between 56.5 and 67 mbsf is dominated by diamictite (Facies 10 and 9), with a thin interstratified sandstone and mudstone at the top of the motif (Facies 3). The Motif 2 example between 563.3 and 537.82 mbsf shows a wide range of ice retreat facies followed by ice advance facies overlying the basal diamictite (Facies 10). Prominent in the middle of the cycle is diatomite (Facies 1b, in this example occurring with Facies 2 mudstone). The example of Motif 3 between 1 066.4 and 1 053.3 mbsf also includes a range of ice-retreat facies overlain by ice advance facies, but is dominated by terrigenous sediment.

interstratified diamictites (Facies 9 & 10), and the sequence upward through the cycle is generally into rhythmically interlaminated mudstone and sandstone (Facies 5), interstratified mudstone and sandstone (Facies 3), and finally into mudstone (Facies 2). Conglomerate (Facies 7) and mudstone with dispersed clasts (Facies 4) also occur with diamictites and interstratified mudstones and sandstones in the proglacial retreat phase. Facies often change vertically through any combination of the above. These units represent retreat of the ice but with considerable submarine outwash and mass-flow deposition. This association of facies, and the apparent lack of bioturbation and diatoms, suggests that the environment had high sedimentation rates principally of fine-grained material in relatively deepwater settings influenced by ice rafting. The succeeding ice-advance portion of the motif tends to be either absent, thinner (truncated or more condensed?), or represented by mudstone with clasts (Facies 4) or stratified diamictite (Facies 9).

DIAGENESIS

This section provides a general description of the major diagenetic features observed during description

of the AND-1B core. These features were observed during visual core description and during microscopic examination of smear slides, and are noted in the PSICAT logs. The general stratigraphic distribution of these features is also described here.

The two major diagenetic features observed in the AND-1B core are carbonate cements and nodules and pyrite cements and nodules; minor features include a crystalline white non-carbonate material (most commonly occurring as fracture fill) and possible siderite. Each of these is discussed separately below.

CARBONATE CEMENTATION

Carbonate cements occur in a variety of forms: disseminated cement, millimetre-scale spherical nodules, centimetre-scale micritic beds or concretions, and vein/fracture fills. In general, the distribution of carbonate cement is linked to the lithology of the host sediment, being more abundant in the diamictites and finer-grained terrigenous clastics (clayey siltstones, silty claystones, and sandy mudstones) and less abundant in the diatomites and volcanic sediments. When examined in more detail than will be presented here, however, the abundance of carbonate cement

varies markedly within each of these lithologies.

Disseminated carbonate cement was noted in the matrix of the diamicts of LSU 1 as shallow as 30 mbsf, and the increased effect of disseminated carbonate cement downcore caused the shift from soft-sediment names (e.g. diamict) to rock names (e.g. diamictite) by ~50 mbsf. Disseminated carbonate cement generally is common to abundant in intervals dominated by diamictites and finer-grained terrigenous clastics (~0–150 mbsf; ~225–375 mbsf; ~460–560 mbsf; ~750–1220 mbsf; and ~1275–1285 mbsf). The abundance of disseminated carbonate cement is more variable in the diatomites, being low to absent at ~150–225 mbsf; common to abundant at ~375–410 mbsf; low to absent at ~410–460 mbsf; and present to common at ~550–587 mbsf. The abundance of disseminated carbonate cement is also variable in the volcanic sediments, being common to abundant at ~110–150 mbsf; present to locally abundant at ~590–760 mbsf; and rare to absent at ~1220–1275 mbsf.

Millimetre-scale small spherical carbonate-cemented nodules (SSCCN on the PSICAT logs) were observed only at 141–145 mbsf in the AND-1B core, where the host lithology is a volcanic sandstone. Similar carbonate nodules were described from the Cape Roberts 2/2A core, also hosted by sandstones. However, the SSCCN were distributed over a larger range of depths in the Cape Roberts 2/2A core.

Carbonate cement is concentrated locally into micritic beds or centimetre-scale concretions, most commonly within intervals of diatomite. These include a micritic bed within a silty claystone at ~224.6 mbsf; carbonate-cemented diatomite at ~292.2 m; two intervals of carbonate-cemented diatomite at 405–407 mbsf; five intervals of carbonate-cemented diatomite at 425–434.5 mbsf; carbonate-cemented diatomite at ~449.5 mbsf; three intervals of carbonate-cemented diatomite at 571–574 mbsf; and two intervals of carbonate-cemented volcanic clayey siltstone at 584–588 mbsf. These occurrences emphasize the heterogeneity in distribution of carbonate cement, because some of the host diatomites and the host volcanic silty claystone are relatively poor in disseminated carbonate cement.

Carbonate cement is also present as vein and fracture fills distributed throughout the core. However, these fracture fills are best developed below 600 mbsf, where both intricate web-like fracture networks and decimetre-long, millimetre-wide discrete fractures are present. In addition, the diamictites below ~900 mbsf commonly contain fractures that rim and extend from large clasts, suggesting that the fractures developed in response to shearing and slight rotation of the clasts.

PYRITE CEMENTATION

Pyrite cements and precipitates occur in a variety of forms: disseminated pyrite and pyritic grain coatings, concentrated pyrite cement, and pyrite nodules and concretions. All of these forms are rare to absent

above ~400 mbsf, but are common to abundant (and locally dominant) below that level.

Pyritic grain coatings are common to abundant in the volcanic sediments at ~115 mbsf, but are absent to rare in the other volcanic-dominated intervals above 400 mbsf. Diffuse pyritic burrow mottles are common to abundant in the diatomite at ~200 mbsf, but are absent to rare in the other diatomites above ~400 mbsf.

Below ~400 mbsf, pyrite is common to abundant, and locally overprints the sediments to the point of obscuring sediment texture and stratification. This pyritic signal overprints all lithologies, although the intensity of pyrite cementation does vary somewhat with the nature of the host lithology; volcanic sediments generally are most intensely affected by pyritisation. From ~400 to ~550 mbsf, pyrite is present in disseminated form and as minor grain coatings; at ~550 mbsf, pyrite nodules and significant pyritisation of individual laminae/beds are first observed within a terrigenous-rich diatomite. Pyrite cement and pyritic grain coatings are especially abundant in the volcanic interval at ~590–760 mbsf; included in this interval are the first occurrences of depositional stratification deformed or disturbed by the growth of extensive pyrite cement (from ~709 to ~760 mbsf). Disseminated pyrite cement, concentrated pyrite cement, and pyrite nodules and lenses are common to abundant in all lithologies below 760 mbsf, and overprint the interval at 1168–1280 mbsf so strongly that original sediment textures, bedding relationships, and grain compositions are difficult or impossible to identify. The pyrite overprint does decrease below ~1280 mbsf.

MINOR DIAGENETIC FEATURES

Two additional diagenetic components were identified during description of the AND-1B core: a crystalline white, non-carbonate material and a dusky red material. The crystalline white material does not react with 10% HCl, and is tentatively interpreted as a zeolite. This material occurs most commonly as fracture fills, but also forms grain coatings and discrete laminae at ~822–823 mbsf. Below ~660.84 mbsf, this material fills fractures that are located close to, and between, fractures filled with carbonate; this close spatial association of two different fracture fills suggests a multi-generational history of fracturing and precipitation.

The second minor diagenetic component identified during core description is a dusky red material, which was observed below ~1002 mbsf. This material forms well-defined, centimetre-thick bands in diamictites, sandstones, and mudstones, as well as diffuse decimetre-thick intervals in silty claystones and sandy mudstones. Smear slides of these intervals show the presence of disseminated carbonate cement, suggesting that the dusky red component is diagenetic siderite.

DEFORMATION

This section provides a general description of the major deformational features observed during visual description of the AND-1B core. These features are noted in the PSICAT logs, although more detailed discussions of these features and their stratigraphic distributions are contained in Wilson T. et al. (this volume).

The major deformational features identified in the AND-1B core are fractures, faults, and soft-sediment deformational features. In many cases, fractures and faults were identified together; however, they will be discussed separately here.

FRACTURES

Fracturing is present to common or abundant in much of the core, but the style of fracturing changes somewhat downcore. The stratigraphic distribution and/or intensity of fracturing appear to be linked only weakly to the lithologies present, so that the overall distribution of fracturing is irregular.

Above ~650 mbsf, fractures generally are present in millimetre- to centimetre-spaced anastomosing networks, usually oriented at relatively low angles with respect to original stratification. In some cases, slight movement on these fractures, or associated faults, has physically intermixed two or more lithologies; in other cases, this disturbance has produced a subtle colour mottling or 'brecciated' appearance within a single lithology. Intervals of volcanic sediment generally are influenced less by this style of deformation than intervals of diamictite, diatomite, or finer-grained terrigenous clastics. However, the distribution of fracturing can be very different for two intervals of a single lithology; for example, fracturing is common to abundant in the diatomites and diamictites at ~150–200 mbsf, whereas the same lithologies have few to no fractures at ~400–460 mbsf and ~330–360 mbsf, respectively.

Discrete single fractures are also present above ~650 mbsf, but are relatively rare. Those that do exist tend to be short (less than a few centimetres) and non-branching.

A more diverse assemblage of fracture types is present below ~650 mbsf than above that level, but identifying the fractures is complicated by the stronger pyrite overprint. Anastomosing fracture networks are still present, but appear to occur more frequently in the finer-grained terrigenous clastic intervals than in the diamictites and volcanics. However, the strong pyrite overprint on the volcanic sediments and some of the diamictites may obscure fracture networks in those lithologies.

Three additional types of fractures are present below ~650 mbsf: discrete long and complex fracture systems (sometimes described as 'fracture webs'), discrete long single fractures, and fractures emanating from larger clasts in the diamictites. The long and complex fracture systems are a few

centimetres to a decimetre long and composed of multiple interweaving fractures, each generally of sub-millimetre width. These 'fracture webs' generally have a white fill, which usually is carbonate. The discrete long fractures are subvertical to vertical, and range from a few centimeters to several decimeters in length; most are a few millimetres wide or less, although several have voids approaching 1 cm in diameter. The discrete long fractures have fills that range from white (carbonate or ?zeolite?) to greenish black (?pyrite?); the widest ones have fills that are stratified (*i.e.* multi-generational). The third type of fracture is highlighted by white fill, which also rims the clast where the fracture originates; this pattern suggests that the diamictite was fractured as the clast was sheared and rotated.

FAULTS

Much of the faulting in the AND-1B core is linked to the fracturing described previously. However, additional faulting of other styles is developed separately from the fracturing, so that the diversity of the faults present changes somewhat downcore. As was the case for the fractures, the increased intensity of pyritisation downcore makes it more difficult to identify certain types of faults in the lower half of the core.

In general, faulting is most abundant at ~100–400 mbsf and ~800–950 mbsf, least abundant at ~400–800 mbsf, and intermediate in abundance below ~1000 mbsf. In addition to structural/tectonic controls, this distribution of deformation appears to be affected by (1) the stratigraphic distribution of lithologies, (2) the distribution of stratification within those lithologies (since offsets are more easily recognised in stratified deposits), and (3) the distribution and intensity of diagenetic pyritisation.

Closely spaced conjugate fault sets, with millimetre-scale offset, are probably the most common fault type in the recovered core. These generally accompany the anastomosing fracture networks; as a result, these fault sets appear to be more abundant above ~650 mbsf than below that level. As mentioned previously, though, the strong pyrite overprint may obscure similar fault and fracture sets below ~650 mbsf.

Additional faulting is present as low-angle thrust faults and as low- to high-angle normal faults. Low-angle thrust faulting is most evident along contacts between different lithologies, especially near the bases of diamictites. In these cases, the subjacent lithologies are physically mixed by the combination of fracturing and low-angle shearing. Qualitatively, this type of faulting appears more abundant above ~400 mbsf, where diamictites are repeatedly interbedded with other lithologies.

Low- to high-angle normal faults are distributed throughout much of the core above ~400 mbsf and below ~800 mbsf. Offsets on these faults generally are less than a few centimetres. Faults above ~400 mbsf

tend to be relatively short (a few centimetres in length or less); faults below ~800 mbsf include ones that are similarly short, as well as some that are much longer (up to several decimetres long).

SOFT-SEDIMENT DEFORMATION

The predominant indicator of soft-sediment deformation in the AND-1B core is convolute bedding, which varies in scale from a few centimetres or less to deformed intervals with recumbent folds that are at least several decimetres thick.

A preliminary qualitative assessment shows that convolute bedding is most abundant at ~110–150 mbsf (diamictites, volcanic sandstones, and finer-grained terrigenous clastics); ~365–375 mbsf (intermixed diamictites, finer-grained terrigenous clastics, and minor diatomite); ~515–525 mbsf (interbedded diamictites, sandstones, and finer-grained terrigenous clastics); ~600–650 mbsf (interbedded volcanic sediments); ~700–760 mbsf (interbedded volcanic sediments); ~815–880 mbsf (finer-grained terrigenous clastics with minor diamictites); ~1215–1225 mbsf (interbedded diamictites, volcanic sandstones, and finer-grained terrigenous clastics); and ~1250–1274 mbsf (interbedded volcanic sandstones and volcanic siltstones). These intervals all contain at least one of three lithologies—diamictite, volcanic sandstone/siltstone, or stratified terrigenous mudstones/siltstones/sandstones—indicating the role of rapid deposition and/or loading in destabilizing sediment. However, other intervals within the recovered core contain one or more of these lithologies without significant soft-sediment deformation; a more detailed study and better understanding of these differences in syndepositional and early post-depositional behaviour may be very useful for refining depositional models and improving the palaeoenvironmental interpretations of this core.

Acknowledgements—The ANDRILL project is a multinational collaboration between the Antarctic programmes of Germany, Italy, New Zealand and the United States. Antarctica New Zealand is the project operator and developed the drilling system in collaboration with Alex Pyne at Victoria University of Wellington and Webster Drilling and Enterprises Ltd. Antarctica New Zealand supported the drilling team at Scott Base; Raytheon Polar Services Corporation supported the science team at McMurdo Station and the Crary Science and Engineering Laboratory. The ANDRILL Science Management Office at the University of Nebraska-Lincoln provided science planning and operational support. Scientific studies are jointly supported by the US National Science Foundation, NZ Foundation for Research, Science and Technology and the Royal Society of NZ Marsden Fund, the Italian Antarctic Research Programme, the German Research Foundation (DFG) and the Alfred Wegener Institute for Polar and Marine Research.

REFERENCES

- Fielding C.F., Naish T.R., Woolfe K.J., & Lavelle M.A., 2000. Facies Analysis and Sequence Stratigraphy of CRP-2/2A, Victoria Land Basin, Antarctica. *Terra Antarctica*, **7**, 323–338.
- Fielding C.F., Naish T.R., Woolfe K.J., Barrett P.J., van der Meer J.J.M., & Laird M.G., 2001. Facies architecture of the CRP-3 drillhole, Victoria Land Basin, Antarctica. *Terra Antarctica*, **8**, 217–224.
- Moncrieff A.C.M., 1989. Classification of Poorly Sorted Sedimentary Rocks. *Sedimentary Geology*, **65**, 191–194.
- Naish T.R., Levy R.H., Powell R.D., & MIS Science and Operations Team Members, 2006. *Scientific Logistics Implementation Plan for the ANDRILL McMurdo Ice Shelf Project*. ANDRILL Contribution 7, University of Nebraska-Lincoln, Lincoln, NE. 117 p.
- Powell R.D. & Cooper J.M., 2002. A Glacial Sequence Stratigraphic Model for Temperate, Glaciated Continental Shelves. In: Dowdeswell, J.A. & O'Cofaigh C. (eds.) *Glacier-Influenced Sedimentation on High Latitude Continental Margins*. *Geol. Soc. Spec. Pub.*, **203**, Geological Society of London, 215–244.
- White J.D.L. & Houghton B.F., 2006. Primary Volcaniclastic Rocks. *Geology*, **34**, 677–680.